Soil Organic Carbon Dynamics under Short-term Conservation Agriculture Cropping Systems in Cambodia

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Biographical Sketch

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Dedication

To my dearest parents, Saroeun Hok and Pao Chhin, for their love, support and guidance.

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Table of Contents

List of Figures

List of Tables

Abstract

Conservation agriculture (CA) constitutes a potential set of management practices to restore soil total N (STN), soil organic C (SOC) and its labile fractions (i.e., particulate organic C-POC, hot-water extractable organic C-HWEOC, permanganate oxidizable C-POXC), to increase soil enzyme activities and to enhance soil aggregation. After five years, CA averagely increased SOC stocks over CT at 0-5 cm by 10%, 20% and 18%, STN stock by 8%, 25% and 16% , POC stocks by 22%, 20% and 78%, HWEOC stocks by 61%, 55% and 53%, and POXC stocks by 23%, 21% and 32% for rice-, soybean- and cassava-based cropping systems (RcCS, SbCS and CsCS, respectively). In general, no noticeable changes in the subsoil layers were observed. When monitoring after three years, stocks of SOC fractions (i.e., mineral-associated organic C-MAOC, pyrophosphate extractable organic C-PEOC, chemically stabilized organic C-CSOC) were almost constant in each depth among land uses, except MAOC in SbCS and PEOC in CsCS at 0-5 cm where CA showed significant effects. In contrast, β-glucosidase activity was 18%, 28% and 49% greater in CA than in CT soils at 0-5 cm under RcCS, SbCS, CsCS, respectively, whereas arylsulfatase activity under CA was greater than CT by 36% in SbCS and 39% in CsCS. The proportions of large macroaggregates (8-19 mm) at 0-5 cm under CA averagely increased 23%, 39% and 53% in RcCS, SbCS and CsCS, respectively, and consequently increased soil aggregation indices (i.e., mean weight diameter-MWD, mean geometric diameter-MGD and aggregate stability index-ASI) compared with those under CT. On average, and across all aggregate size classes, CA accumulated SOC concentrations over CT by 11%, 7% and 6%, total N concentrations by 3%, 11% and 15% and POXC concentrations by 18%, 20% and 15% for RcCS, SbCS and CsCS, respectively, at 0-5 cm. These increases led to positive correlations between large macroaggregate-associated SOC and soil aggregation indices in 0-5 cm depth in

the three cropping systems. The results of CP-MAS ^{13}C NRM measurement showed that humic acid from soils under CT tended to have higher proportions of aliphatic C than under CT while in reverse for aromatic C. This supports the promotion of CMI under CA indicating greater lability of SOC.

In conclusion, short-term CA practices in the three cropping systems increased the storage of STN, SOC and labile SOC pool and enhanced soil enzyme activities in the surface soils with potential effects in the subsoil layers through increased proportion of large macroaggregates and soil aggregation indices resulting from high and diversified biomass-C inputs and the absence of physical soil disruption.

CHAPTER 1

General Introduction

1.1 Research Justification

Soils can be either a source of or a sink for atmospheric CO_2 depending on land use and management (Lal, 2003b, 2010). Agricultural management practices play a substantial role in soil organic C (SOC) dynamics (Chivenge, Murwira, Giller, Mapfumo, & Six, 2007; Lal, 1997; Six et al., 2002). The SOC sequestration increase sustains soil quality and enhances crop productivity (Lal, 2006; Reeves, 1997) due to its close association with a wide range of soil processes and functioning (Smith, Petersen, & Needelman, 1999) including soil physical, chemical and biological properties (Ayuke et al., 2011; Brévault, Bikay, Maldès, & Naudin, 2007; Lal, 2008b; Lienhard et al., 2013; Sá et al., 2009; Six, Bossuyt, Degryze, & Denef, 2004; Tisdall & Oades, 1982). A decline in SOC due to the conversion of natural vegetation into agricultural land is a common phenomenon (Lal, 2002). This decline results from a reduction in organic matter inputs and soil physical disruption. Conventional tillage (CT) and crop residue removal from agricultural land has been practiced for decades and detrimentally affects soil productivity and sustainability (Farooq, Flower, Jabran, Wahid, & Siddique, 2011; Franzluebbers, 2008; Govaerts et al., 2009). CT accelerates decomposition of young and previously stable SOC through soil aggregate disruption that stimulates soil microbial biomass and activity (D. Guo, Li, Li, Wang, & Fu, 2013; Reicosky, Kemper, Langdale, Douglas, & Rasmussen, 1995; Sá et al., 2013; Shibu, Van Keulen, Leffelaar, & Aggarwal, 2010), and affects soil drying and wetting (Six et al., 2004). Several studies have indicated SOC depletion under CT in the tropical soils (Lienhard et al., 2013; Sá et al., 2013; Salinas-Garcia, Velazquez-Garcia, & Rosales-Robles, 2000; Scopel, Findeling, Guerra, & Corbeels, 2005).

Conservation agriculture (CA) has been practiced for four decades and increasingly adopted (Friedrich, Derpsch, & Kassam, 2012) to decrease annual expansion of soil degradation and crop productivity loss. It holds tremendous potential to create sustainable agriculture based on the application of its three key principles: (a) minimum mechanical soil disturbance (no-till) restricted to sowing rows, (b) permanent soil cover by organic mulch, and (c) crop species diversification (i.e. association or rotation) (FAO, 2008). SOC dynamics under CA systems are driven by the balance between C inputs via crop residues and C outputs via microbial oxidation (Davidson & Janssens, 2006; Lal, 2004b; Powlson, Prookes, & Christensen, 1987). It is extremely difficult to substantially sequester SOC in arable soils without massive supplies of organic materials (Powlson et al., 2011). These improved no-till (NT) practices in rotation or association with diversified crop species that utilize more of the available growing periods aim to enhance soil quality, restore SOC and increase crop productivity (Díaz-Zorita, Buschiazzo, & Peinemann, 1999; Farooq et al., 2011; Govaerts et al., 2009; Sá et al., 2014) resulting from the absence of soil aggregate disruption (Feller & Beare, 1997) and the increased amount, quality and frequency of biomass-C inputs (Batlle-Bayer, Batjes, & Bindraban, 2010; Ogle, Breidt, & Paustian, 2005; Ogle, Swan, & Paustian, 2012; Virto, Barré, Burlot, & Chenu, 2012) that create positive C and N budgets and accentuate C and N transformation and flow (Boddey et al., 2010; Sá et al., 2013). Greater SOC accumulation in tropical soils under NT cropping systems based on a diversity of cash crops or in association with cover crops compared with CT has been reported (Bayer, Martin-Neto, Mielniczuk, Pavinato, & Dieckow, 2006; Lienhard et al., 2013; Neto et al., 2010; Sá et al., 2013; Scopel et al., 2005). SOC stored in the deeper soil layers may be in more stable forms (Angers & Eriksen-Hamel, 2008) and its levels might be enhanced by the changes in vegetation to deep-rooting crops that significantly affect the vertical distribution of SOC deep in the soil profile, acting as a potential C sink (Jobbágy & Jackson, 2000). Séguy, Bouzinac, and Husson (2006) reported that SOC in the subsoil was sequestered by higher SOC rhizodeposition of the deep rooting systems such as Congo grass (*Brachiaria ruziziensis*), sorghum (*Sorghum bicolor*) and *Crotalaria spp*. Thus, CA practices provide good support of SOC sequestration.

Short-term changes in total SOC as a result of soil management practices are often difficult to detect (Zotarelli, Alves, Urquiaga, Boddey, & Six, 2007). To assess SOC dynamics under short-term CA, it might be critical to separate SOC into fractions isolated by physical (particulate organic C - POC, mineral-associated C - MAOC) and chemical (i.e., hot-water extractable C - HWEOC, permanganate oxidizable C - POXC, pyrophosphate extractable organic C - PEOC, chemically stabilized organic C - CSOC) methods and to monitor enzymatic activities. Labile pools and enzymatic activities have recently received more attention due to their sensitivity to short-term changes in soil management practices so they could be served as sensitive indicators. The measurement of these fractions provides a good assessment of potential SOC sequestration. Physical fractionation is a useful tool to interpret the SOC dynamics by providing a rough differentiation between active, intermediate and passive SOC pools, and also to assess the impact of soil management practices on dynamics (Cambardella & Elliott, 1994; Christensen, 1992; Six, Elliott, & Paustian, 1999) and quantitative changes (Bayer, Martin-Neto, Mielniczuk, & Ceretta, 2000) in SOC. In general, SOC is physically fractionated to two fractions, POC and MAOC. POC is a sensitive C fraction to detect short-term changes in SOC due to land use and management (Cambardella & Elliott, 1992; Freixo, Machado, dos Santos, Silva, & Fadigas, 2002) whereas MAOC is a stable fraction related to SOC associated with silt- and clay-size fractions (Bayer, Martin-Neto, Mielniczuk, Pillon, & Sangoi, 2001; Sá et al., 2001). Tivet, Sá, Lal, Borszowskei, et al. (2013) indicated that the conversion of native vegetation to cultivated land under CT reduced POC and MAOC fractions in a tropical red Latosol while intensive NT cropping systems with diverse crop species association or rotation restored these two physical size fractions of SOC. In addition to physical isolation, HWEOC, POXC, PEOC and CSOC are chemically isolated. HWEOC constitutes the readily-decomposable SOM (Ghani, Dexter, & Perrott, 2003) and responds rapidly to changes in C supply (Jinbo, Changchun, & Wenyan, 2006). The dissolved organic C, microbial biomass C, soluble soil carbohydrates and amines are all extracted from soil during the extraction of HWEOC (Ghani et al., 2003). Similarly, POXC is also defined as labile SOC and related to soil microbial activity including soil microbial biomass C (MBC), soluble carbohydrate C and total C (Weil, Islam, Stine, Gruver, & Samson-Liebig, 2003). Several studies have found positive relationships between MBC and HWEOC (Ghani et al., 2003; Ghani, Müller, Dodd, & Mackay, 2010; Sparling, Vojvodić-Vuković, & Schipper, 1998), between MBC and POXC (Culman et al., 2010; Melero, López-Garrido, Murillo, & Moreno, 2009) and between SOC and labile pools (i.e. HWEOC and POXC) (Culman et al., 2012; Sá et al., 2014; Tirol-Padre & Ladha, 2004; Weil et al., 2003). This labile SOC pool is enhanced by NT, cropping intensity and rotations and increased SOC pool size. Soil enzymes involve in organic matter mineralization through a wide range of metabolic processes in the soil system (María, Horra, Pruzzo, & Palma, 2002) by providing information about microbial status and soil physicochemical conditions (Sinsabaugh et al., 2008), and respond to soil management changes more quickly than other soil quality indicators (Dick, 1994; Ndiaye, Sandeno, McGrath, & Dick, 2000). Arylsulfatase (EC 3.1.6.1) involves in S cycling and catalyzes the hydrolysis of organic sulfate esters (M. A. Tabatabai & Bremner, 1970). High organic C inputs constitute a principal reservoir of sulfate esters (Dick, Pankhurst, Doube, & Gupta, 1997). β-glucosidase (EC 3.2.1.21) plays a role in the C cycle and is closely related to the transformation and accumulation of organic matter (Wang & Lu, 2006). These two soil enzymes are associated with NT and biomass-C inputs. Green, Stott, Cruz, and Curi (2007) found that β-glucosidase activity were greater in NT soil compared with disk plow soil in the tropical Savannah. Thus, the combination of SOC fractions and soil enzyme activities under NT might provide the valuable information about the pathway to sequester C from the atmosphere to soils and to decrease the release of SOC back to the atmosphere.

The increase in SOC stabilized in the soil under NT cropping systems may remain a great potential for SOC sequestration. SOC stabilization is controlled by three main mechanisms: (a) chemically innate recalcitrance, (b) protection through interaction with minerals, and (c) occlusion in aggregates (Mikutta, Kleber, Torn, & Jahn, 2006). Soil aggregation has major effect on soil C cycling, root development and soil resistance to erosion (Kay, 1998) and composes of primary mineral particles and organic binding agents (Tisdall & Oades, 1982). The formation of stable soil aggregates is related to mineralogy, texture (Feller & Beare, 1997) and SOC (Dutartre, Bartoli, Andreux, Portal, & Ange, 1993; Tisdall & Oades, 1982). Aggregate-associated SOC provides strength and stability, counters the impact of destructive forces and is an important reservoir of soil C because of being physically protected from microbial and enzymatic processes (Bajracharya, Lal, & Kimble, 1997). The continuous practices of CT damage soil structure by breaking down soil aggregates (Zotarelli et al., 2007) and cause a reduction in the proportions of soil macroaggregates and consequently exposing SOC to microbial oxidation. Thus, SOC sequestration in soils under NT cropping systems is largely influenced by soil aggregation. NT cropping systems in rotation or association with cover crops significantly enhances aggregate stability, macroaggregates-occluded microaggregates and SOC protection compared with CT (Barreto et al., 2009; Denef, Six, Merckx, & Paustian, 2004) due to their high biomass-C inputs that generate a wide range of aggregating agents such as fungal hyphae, microbial bio-products (Haynes & Francis, 1993), root exudates (Guggenberger, Frey, Six, Paustian, & Elliott, 1999) and plant derived polysaccharides (Feller & Beare, 1997). This increased soil aggregate stability through NT and aggregating agents enhances the ability of soil to protect and sequester SOC leading to sustainable soil management.

The development of annual upland crops (i.e., maize, cassava, soybean and mungbean) soared from ~ 217K ha in 2003 to ~ 716K ha in 2012 (MAFF, 2013) to satisfy the needs of growing population in Cambodia. The agricultural land expansion for the production of these crops has gradually diminished forest areas and exacerbated the growing concern over soil degradation (Belfield, Martin, & Scott, 2013; Hean, 2004; Poffenberger, 2009; UNDP, 2010) posing a serious threat to sustained agricultural productivity and food security (CDRI, 2014; UNDP, 2010). Over 40% of the Cambodian population is affected by land degradation, representing 78K km^2 or 43% of total land area (Bai, Dent, Olsson, & Schaepman, 2008). The figures might be higher in the last few years. The impacts of CA or its different component practices have been reviewed to potentially sequester C into the agricultural soils in various regions (Corsi, Friedrich, Kassam, Pisante, & Sà, 2012; Govaerts et al., 2009; Lal, 2006; Luo, Wang, & Sun, 2010; Ogle et al., 2012). Thus, the challenges to apply this improved set of agricultural management practices to sequester SOC and consequently to enhance soil and crop productivity is necessary to define sustainable agriculture development.

1.2 Research Objectives

The effects of CA on SOC dynamics and its protection mechanisms in cropland soils in Cambodia are still scarce so rigorous empirical evidence to fingerprint an appropriate soil management practices and crop rotation scheme to promote SOC recovery is necessarily needed.

There might be no doubts that long-term CA can be a set of effective agricultural practices for sequestering total SOC but short-term changes are still debatable. Therefore, this short-term CA study was carried out (a) to assess the magnitude of changes in total SOC and its fractions (i.e., POC, MAOC, HWEOC, POXC, PEOC, CSOC) and soil enzymatic activities (i.e., arylsulfatase, β-glucosidase) after conversion of RV to CT for five years and the potential of CA to recover SOC close to an antecedent level under adjacent RV, and (b) to quantify the impacts of CA on the SOC protection mechanism using aggregate size distribution and aggregate-associated total SOC, total N and POXC after three-year practices, and the relationship between soil aggregation indices and aggregate-associated SOC in three distinct upland cropping systems (i.e., rice, soybean, cassava) in a savanna tropical agro-ecosystem of Cambodia.

1.3 Research Hypothesis

Given the above objectives, we hypothesized that the intensive NT systems (i.e., diversity of cover/relay crops and high annual biomass inputs) within five years will be a starting step to sequester SOC in the topsoil compared with CT in the three cropping systems by reducing physical soil disruption and creating the C flow to support C storage, especially the labile SOC pool and soil enzymes that will be served as indicators to estimate SOC dynamics over longer-term trends. We expect that CT of heavy clayed Oxisols has a low impact on the original native SOC stocks and its SOC level will be slightly increased due to the spread of crop residues after harvesting main and preceding crops. This research will also test the hypothesis that increasing soil aggregate stability and enhancing the formation of large macroaggregates by intensive NT systems is the underlying mechanism driving SOC dynamics and is judicious management strategy leading to increased aggregate-associated SOC, total N and POXC compared with CT through continuous provision of aggregate binding agents from crop residues.

CHAPTER 2

Literature Review

2.1 Conservation Agriculture Practices and Adoption

The continuous application of CT practices with crop residue removal from agricultural land has been implemented for decades causing negative effects on soil productivity and sustainability (Farooq et al., 2011; Franzluebbers, 2008; Govaerts et al., 2009) by increasing CO_2 emission to the atmosphere and lowing the total C sequestration held within the soil, thus cannot ensure the sustainable management of agro-ecosystems. Over the last few decades, a general trend in the soil degradation has been noticed, which is one of the most pertinent constraints occurring in agricultural land causing a reduction of soil's actual and potential productivity and posing a serious threat to agricultural sustainability and environmental quality (Lal, 1993). In intensified cropping systems, CT and inadequate organic matter inputs have a heavy toll on maintaining the soil integrity. The challenges to develop appropriate agricultural management practices to sequester soil C and sustain soil and crop productivity have become more intense in recent years. The secret to combat soil degradation leading to sustainable agriculture is to never allow the soil to be bare and unprotected, but to ensure that the soil surface is always covered with growing plants or the dead mulch (Brown, 2008).

Conservation agriculture (CA) has been practiced for about four decades and spread widely (Friedrich et al., 2012) and has become a hegemonic paradigm in sustainable agricultural development because it constitutes the effective tool to create sustainable crop production intensification with its three key principles: (a) minimum mechanical soil disturbance (no-till), (b) permanent soil cover by organic mulch and (c) diversified crop species rotation or association (FAO, 2008). These principles seem to be applicable to a wide range of crop production systems from low-yielding, dry rainfed to high-yielding irrigated conditions (Govaerts et al., 2009). CA has been practiced to decrease the expansion of soil degradation and crop productivity loss while conserving the environment. This improved set of agricultural management practices that utilizes more of the available growing periods aims to restore SOC and enhances soil and crop productivity (Díaz-Zorita et al., 1999; Farooq et al., 2011; Govaerts et al., 2009; Sá et al., 2014) resulting from the absence of soil aggregate disruption (Feller & Beare, 1997) and the increased amount, quality and frequency of biomass-C inputs via crop residues (Batlle-Bayer et al., 2010; Ogle et al., 2005; Ogle et al., 2012; Virto et al., 2012). Based on its capability of building sustainability into agricultural production systems, the adoption of CA or its components is increasing in several parts of the world as an alternative to both conventional and organic agriculture. According to global assessments of available figures, CA or (at least) NT systems have been increasingly adopted on total cultivated land areas of ~ 72 million ha in 2001 (Derpsch & Benites, 2003), ~ 96 million ha in 2004 (Derpsch, 2005), ~ 106 million ha in 2008 (Derpsch & Friedrich, 2009) and ~ 155 million ha in 2013 (FAO, 2014). The majority of the adopted land areas are in South America and North America while it is limitedly adopted in Africa and Asia where small holder, resource-constrained farmers are dominated in these two continents. The applicability and adoption of CA are most likely to succeed in large-scale rather than small-scale farming. In the case of Africa, Giller, Witter, Corbeels, and Tittonell (2009) argued that the scientific evidence to empirically support the claims made for CA is inconclusive, and that CA does not fit within the majority of current smallholder farming systems in Africa. These constraints might also exist in Asia, particularly in Cambodia where CA is a relatively new concept and has been introducing to sustainably intensify crop production while having considerable environmental benefits.

In Cambodia, the land expansion for upland crop production (i.e., maize, cassava, soybean and mungbean) soared from ~ 217K ha in 2003 to ~ 716K ha in 2012 (MAFF, 2013) due to rural population growth and has gradually diminished forest areas and exacerbated the growing concern over soil degradation (Belfield et al., 2013; Poffenberger, 2009; UNDP, 2010). Most identified soil types have a rather low natural fertility and a process of soil degradation is apparent (Johnsen & Munford, 2012). Over 40% of the Cambodian population was affected by land degradation, representing 78,000 km^2 or 43% of total land area (Bai et al., 2008). CT and high inputs of chemical fertilizers and pesticides have been widely implemented to intensify upland crop production in the country and have increased the expansion of degraded upland soils, which might lead to an increase in the total degraded land area in the last few years. Thus, the increasing concern over the long-term ecological and economic impacts has been raised for sustainable crop and soil management. To combat the loss of agricultural productivity in the uplands, to ensure sustainability of agronomic land use and to intensify crop production, the Ministry of Agriculture, Forestry and Fisheries of Cambodia under the support of Agence Française de Développement (AFD) and Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD) initiated a research and development (R&D) program on direct seeding mulch-based cropping (DMC) systems to create and propose sustainable intensification of upland cropping systems in the country (Boulakia, Kou, San, Leng, & Chhit, 2008). DMC is a promising option of sustainable soil management in the tropics due to the absence of soil disruption and the permanent soil cover by a mulch of crop residues (Scopel et al., 2005). DMC systems are now gathered under the broad concept of CA. This set of agricultural management practices provides a significant effect on soil processes and functioning under intensified cropping systems in the upland area of Cambodia where soils intensively plowed and cropped and the majority of crop residues removed from the fields. The R&D program has implemented in the 45 ha land area in Bos Khnor Research Station and expanded to smallholder farmers in Battambang and Kampong Cham provinces covering 375 ha of upland, rainfed cropping systems (SOFRECO, 2013). Although CA ensures sustainable crop production intensification through soil quality improvement and SOC sequestration, the adoption of CA among farmers in Cambodia is still limited due to lack of knowledge, capital intensive and conclusive empirical evidence.

2.2 Contribution of Tillage-induced Soil Carbon Loss to Global Warming

The marked increase in greenhouse gas emissions in recent years has been considered as a serious threat to global warming. The present atmospheric CO_2 increase is dominantly caused by anthropogenic emissions of CO_2. Total anthropogenic emissions of C as CO_2 were 6.3 Pg yr^{-1} during the 1980s, 8.0 Pg yr^{-1} during the 1990s and about 9.0 Pg yr^{-1} between 2000 and 2005 (Lal & Follett, 2009). Soil is one of important natural reservoirs of C and it was estimated to have contributed as much as 55 to 878 Pg of C to the total atmospheric CO_2 (Kimble, Lal, & Follett, 2002). The CO_2 emiision from the soil is the second largest component of the global C cycle and contributes to climatic variation (Reth, Reichstein, & Falge, 2005). The conversion of natural ecosystems into agricultural ecosystems and soil cultivation typically depletes SOC (Don, Schumacher, & Freibauer, 2011; L. B. Guo & Gifford, 2002; Sá et al., 2013; Wei, Shao, Gale, Zhang, & Li, 2013) with the attendant emission of CO_2 into the atmosphere (Lal & Follett, 2009). The increasing annual release of CO_2 contributes growing concerns over global warming and leads to increased strong interest in the role of soils to store C to counterbalance this rising atmospheric CO_2 levels mitigating the risks of global warming.

Soils can act as either a sink for or a source of atmospheric CO_2 depending on the changes in land management practices (Lal, 2003b, 2010). Agricultural management practices profoundly affect SOC dynamics (Chivenge et al., 2007; Lal, 1997; Six et al., 2002). SOC is considered to play a key role in sustaining soil and crop productivity (Lal, 2006; Reeves, 1997) and controlling belowground system stability (S. Huang, Sun, Rui, Liu, & Zhang, 2010) due to their effects on soil physical (Bhogal, Nicholson, & Chambers, 2009; Guzman & Al-Kaisi, 2011; Tisdall & Oades, 1982), chemical (Hao, Chang, & Lindwall, 2001; Sá et al., 2009), and biological (Ayuke et al., 2011; Bhogal et al., 2009; Brévault et al., 2007; Lienhard et al., 2013; Six et al., 2004; Uphoff et al., 2006) properties. Thus, its loss negatively impacts the soil structure leading to compaction while increasing CO_2 flux from soils to the atmosphere (Bronick & Lal, 2005) and thus affect the global C balance. The tillage of forest or natural grassland soils after conversion to cropland results in the considerable loss of 55 Pg of C from the global SOC pool thereby converted a large fraction of SOC to CO_2 (Pacala & Socolow, 2004). Soil cultivation by continuous CT causes the increased decomposition rate of previously stable SOC due to physical soil disruption that greatly exposes young and stable C to the microbial attack (Lienhard et al., 2013; Reicosky et al., 1995; Sá et al., 2013; Shibu et al., 2010). In addition, CT results a higher contact between soil and crop residues and increases soil temperature, favoring organic matter decay and consequently increasing the CO_2 emission from the soils (La Scala, Lopes, Marques Jr, & Pereira, 2001; Lal, 2003a). Numerous studies in various regions showed the higher CO_2 emission from soils under CT in relation to NT (Al-Kaisi & Yin, 2005; Carvalho et al., 2009; Franchini, Crispino, Souza, Torres, & Hungria, 2007; Fuentes et al., 2012; Liu et al., 2013; Omonode, Vyn, Smith, Hegymegi, & Gál, 2007; Ruan & Philip Robertson, 2013; Ussiri & Lal, 2009). The study of Carvalho et al. (2009) in a very clayed Oxisol in the humid tropics indicated that CT systems had 20% and 22% higher CO_2 emission rates (i.e., soil and root respiration) in dry and wet seasons, respectively, compared with NT, which resulted from disruption of the structural integrity of soil aggregates under CT, accelerating organic matter oxidation and thus increasing CO_2 flux from CT soils to the atmosphere. They emphasized the potential of NT systems to mitigate CO_2 emissions from the soils. In summary, CT exposes more soil to the air, causing SOC to react and escape as CO_2 that may exacerbate the global warming. This CO_2 efflux from soils to the atmosphere results from root respiration and physiological processes of microorganisms involved in the organic matter decomposition.

2.3 Soil Carbon Sequestration under Conservation Agriculture

SOC sequestration is the process of transferring atmospheric CO2 into the soil through crop residues and other organic solids, and in a form that is not immediately reemitted (Olson, 2013; Osman, 2013). SOC sequestration by agricultural land has generated global interest due to its potential impact and benefits for both agriculture and climate change adaptation and mitigation (Olson, Al-Kaisi, Lal, & Lowery, 2014). The nature of NT cropping systems (i.e., cropping sequence, use of relay/cover crops, crop frequency in the sequence) and the variability in biomass-C inputs (i.e., quantity and quality) are the main control of SOC sequestration (Ogle et al., 2005). The persistent practices of conventional farming based on intensive tillage have magnified SOC depletion and detrimental impacts on the crop productivity and environment. SOC loss from the tropical soils through physical soil disruption by CT has been reported (Lienhard et al., 2013; Nascente, Li, & Crusciol, 2013; Sá et al., 2013; Salinas-Garcia et al., 2000; Scopel et al., 2005). Soil C degradation leads to soil quality losses and poses a threat for both agricultural production systems and food security (Lal, 2004a). Concerning over these issues, CA has been adopted for the ultimate vision of sustainable crop production intensification while conserving the soils. In this context, SOC sequestration plays a major role in maintaining soil and crop productivity due to its effect on soil properties. SOC dynamics under CA systems are driven by the balance between C inputs via crop residues and C outputs via microbial oxidation (Davidson & Janssens, 2006; Lal, 2004b; Powlson et al., 1987). Thus, SOC can be sequestered by crop rotations and NT practices with addition of crop residues near the soil surface (Lal, Follett, & Kimble, 2003). SOC might be not only sequestered in the top soil layer but also in the subsoil layers when deep-rooting cover crops are included in the crop rotations. Séguy et al. (2006) reported that SOC in the subsoil could be increased by higher SOC rhizodeposition of the deep rooting systems such as Congo grass, sorghum and *Crotalaria spp.* These cover crops are well adapted to acidic soils and produce high crop biomass which becomes part of the soil as SOC pool. Therefore, investigations of SOC dynamics of agricultural tropical soils can provide valuable information on how to promote C sequestration in such soils (Bayer, Martin-Neto, et al., 2006).

Several studies have been proved that the practices of CA or its components significantly restore SOC. Scopel et al. (2005) studied the five-year impacts of CA with varying levels of surface crop residues retained on the soil surface on changes in soil C dynamics in a semi-arid tropical climate. The results showed that CA treatments accumulated significantly high C concentrations compared with CT at 0-2.5 and 2.5-5 cm soil depths. On average of the two CA with crop residue inputs, and across the two surface soil layers, soils under CA had 77% higher C concentrations than that under CT. CA did not show a significant effect at deeper layers. This was probably due to a short-term period and limited C inputs. In addition, the increase in mulch inputs of maize residues from 1.5 to 4.5 Mg ha^{-1} into the soil resulted in a higher C accumulation of 29% at 0-2.5 cm soil layer. After corrected differences in bulk density, the two CA treatments averagely had 26% (4.75 Mg C ha^{-1}) more C stocks than CT at 0-20 cm depth. This result suggests that biomass-C inputs from crop residues can increased the level of soil C levels over a five-year period compared with CT at 0-5 cm of the soil profile. Similarly, Sá et al. (2013) investigated the effects of NT with diverse biomass-C inputs from residues of various crop species included in the crop rotations on SOC dynamics among native vegetation (NV), NT and CT cropping systems in a tropical Oxisol. After eight years, SOC stock under CT was 30% (14.2 Mg C ha^{-1}) lower than that under NV whereas NT (average of the six NT treatments) stored SOC 20% (6.7 Mg C ha^{-1}) higher than CT in the 0-20 cm soil depth. The increase in SOC in deeper was also observed in soils under NT. Considering 100 cm as a single stratum, soils under NT had 12% (12 Mg C ha^{-1}) higher SOC stocks than that of CT. The SOC stock levels were in an order NV > NT > CT. They concluded that SOC accumulation increased with increaing bimass-C inputs and it was evident that intensive NT cropping systems (high and diversified annul C inputs) had a potential to restore SOC proviously deplted by CT in the stuided tropical climate. The adoption of CA systems increases above- and belowground biomass-C inputs and decreases SOC decomposition rates through increased soil aggregation to protect SOC from decomposers, which leads to SOC sequestration.

To better understand the impacts of agricultural management practices on SOC dynamics, it is necessary to separate SOC into fractions isolated by physical and chemical methods and to also assay soil enzyme activities. These SOC fractions can provide valuable information to estimate SOC dynamics over long-term trends. The SOC pool is highly diverse with contrasting turnover times, and stabilized or protected again microbial decomposition (Lützow et al., 2006). The labile SOC pool (i.e., POC, HWEOC, POXC) is the most rapid turnover times and potentially restored even in a short period. This pool is likely to be more sensitive to soil management practices than total SOC (Campbell, Janzen, & Juma, 1997; Z. Huang, Xu, & Chen, 2008). Physical fractionation is a useful tool to interpret the SOC dynamics by roughly differentiating active, intermediate and passive SOC pools, and to assess the impact of soil management on dynamics (Cambardella & Elliott, 1994; Christensen, 1992; Six et al., 1999) and quantitative changes (Bayer et al., 2000) in SOC. Soil particle-size fractionation plays a crucial role in assessing the soil organic matter (SOM) accessibility (Gregorich, Beare, McKim, & Skjemstad, 2006) and interactions between organic and inorganic soil components in the turnover of SOM (Christensen, 1992, 2001). POC is a labile fraction and a good qualitative indicator to detect changes in SOM due to land use and management (Cambardella & Elliott, 1992; Freixo et al., 2002). POC is a sensitive pool and its changes are directly related to the quantity, quality and frequency of crop residues added to the soil (Diekow et al., 2005; Lienhard et al., 2013; Sá et al., 2001; Vieira et al., 2007). In contrast, MAOC is considered as a stable fraction and less sensitive than POC to land use and management. It reflects the relationship between SOC and silt- and clay-size fractions (Bayer et al., 2001; Sá et al., 2001). It can be changed by physical and chemical soil environment rather than by land use changes (Guggenberger, Christensen, & Zech, 1994) resulting in a lower turnover rate (Feller & Beare, 1997). Results from the study of Tivet, Sá, Lal, Borszowskei, et al. (2013) to assess the magnitude of changes SOC fractions (i.e., POC, MAOC) in a red tropical Latosol indicated that intensive NT cropping systems increased POC and MAOC stocks compared with CT in the 0-20 cm soil layer after eight years. On average, POC and MAOC stocks under NT treatments were 19% (~ 1.3 Mg POC ha^{-1}) and 13% (~ 3.5 Mg MAOC ha^{-1}) higher, respectively, than those under CT. When comparing with NV, the loss rate of POC and MAOC under CT in the 0-20 cm was revealed whereas NT systems showed a recovery trend of POC and MAOC compared with the antecedent levels under NV. They emphasized that NT systems with high biomass-C inputs from crop residues potentially restore POC and MAOC fractions previously depleted by CT.

Labile SOC fractions isolated by the chemical method (i.e., HWEOC, POXC) are more sensitive to agricultural management practices than PEOC and CSOC and respond quickly to changes in C supply. The dissolved organic C, MBC, soluble soil carbohydrates and amines are all extracted from soil during the extraction of HWEOC (Ghani et al., 2003). POXC is also an active SOC pool and it is known that slightly alkaline $KMnO_4$ is used to hydrolyze and oxidize simple carbohydrates, amino acids, amine/amine sugars, and C-compound containing hydroxyl, ketone, carboxyl, double-bond linkages and aliphatic compounds (Loginow, Wisniewski, Gonet, & Ciescinska, 1987). Positive relationships between MBC and HWEOC (Ghani et al., 2003; Ghani et al., 2010; Sparling et al., 1998), between MBC and POXC (Culman et al., 2010; Melero et al., 2009; Weil et al., 2003) and between SOC and labile pools (i.e., HWEOC and POXC) (Culman et al., 2012; Sá et al., 2014; Tirol-Padre & Ladha, 2004; Weil et al., 2003) have been reported. Thus, the increase in these labile SOC pools can be the pathway to sequester SOC. Pyrophosphate is used to extract soil C due to its selective ability to remove Fe and Al-bound organic matter by complexing with di- and trivalent cations (Wattel-Koekkoek, van Genuchten, Buurman, & van Lagen, 2001). Thus, PEOC pool represents the SOC associated with the active forms of Fe and Al. CSOC is known as the passive or refractory SOM pool is organic substances which is resistant to further mineralization (Eusterhues, Rumpel, & Kögel-Knabner, 2005). These two SOC pools are less impacted by short-term land use and management. Tivet, Sá, Lal, Borszowskei, et al. (2013) reported that NT systems associated or rotated with diverse cover crop species had 59% (0.22 Mg C ha^{-1}) higher HWEOC stocks than CT in the 0-20 cm depth in a red tropical Latosol after eight years. The higher stocks were also observed in the deeper soil layers but the significant differences in CSOC stocks were not detected between CT and NT. Stine and Weil (2002) studied the change in POXC concentration under CT and NT in a tropical region of south central Honduras. They found that soils under NT contained 76% higher POXC than CT and POXC was highly correlated with total soil C. They emphasized that changes in total soil C resulted from proportional changes in both active and passive C fractions. In addition, the results also showed the positive correlation between macroaggregate stability and POXC concentration. Thus, less soil disruption and higher biomass-C inputs under NT systems contributes to the greater HWEOC and POXC and consequently enhance soil macroaggregate formation which may protect SOC (Tivet, Sá, Lal, Briedis, et al., 2013). The enzyme activities in soil systems vary primarily due to different amounts of organic matter content and composition, living organisms' activity and intensity of biological processes (Das & Varma, 2011). They are sensitive indicators to provide valuable information on the impact of land use management and cropping systems (Fernandes, Bettiol, & Cerri, 2005; Rabary et al., 2008). Arylsulfatase plays an important role in S cycling and can catalyze the hydrolysis of organic sulfate esters (M. A. Tabatabai & Bremner, 1970) while β-glucosidase in the C cycle ant it is closely related to the transformation and accumulation of SOM (Wang & Lu, 2006). Green et al. (2007) studied the impact of tillage practices on soil biological activity in a red Latosol in the tropical Savannah. They found that β-glucosidase activity in the soil under the NT corn-common bean (*Phaseolus vulgaris* L.) rotation was 82% significantly greater than under disk plow management in the 0-5 cm depth after five years and emphasized that β-glucosidase activity in the topsoil was sensitive to soil management practices. Together with other soil enzymes in their study, it was concluded that NT management improved soil biological properties leading to soil aggregate stabilization. High biomass-C inputs constitute a principal reservoir of sulfate esters, the substrate for arylsulfatase (Dick et al., 1997). The study in a temperate soil by Gajda, Przewłoka, and Gawryjołek (2013) reported the arylsulfatase activity under eight-year NT systems was two- to threefold greater than that obtained under traditional tillage at 0-15 cm soil layer resulting from higher plant residue inputs. They also found a positive correlation between MBC and arylsulfatase activity. It is evident that NT and biomass-C inputs via crop residues significantly affect these two soil enzymes particularly in the soil surface and consequently enhance soil aggregation that is an important mechanism to increase SOC sequestration.

In conclusion, the continuous inputs of biomass-C via crop residues to the soil surface under NT cropping systems potentially restore SOC, its fractions and soil enzyme activities which can be used as good indicators of sustainable soil management.

2.4 Soil Aggregate Stability and Soil Carbon Sequestration

Soil aggregates are composed of primary mineral particles and organic binding agents (Tisdall & Oades, 1982). Soil aggregation has major effect on soil C cycling, root development and soil resistance to erosion (Kay, 1998) and it one of important mechanisms to protect and sequester SOC (Feller & Beare, 1997; Lützow et al., 2006). The formation of stable soil aggregates is related to mineralogy, texture, the quality and quantity of organic matter inputs, exchangeable ions, aluminum and iron oxides, SOC concentration and microbial activities (Bronick & Lal, 2005; Feller & Beare, 1997; Kay, 1998). The proportions of soil water stable aggregates often change rapidly when tillage practices and crop rotations are modified (Angers, Pesant, & Vigneux, 1992). SOC sequestration through aggregation is an important aspect of soil management. The SOC in microaggregates is believed to be protected from degradation and hence relevant for C sequestration. Thus, soil aggregation and SOC accumulation due to physical protection are two intrinsically linked phenomena (Barreto et al., 2009). Aggregate-associated

SOC provides strength and stability and is an important reservoir of soil C because of being physically protected from microbial and enzymatic degradation (Bajracharya et al., 1997). A positive relationship between SOC and soil aggregate stability has been reported in studies from various regions (Briedis, Sá, Caires, Navarro, et al., 2012; Dutartre et al., 1993; Madari, Machado, Torres, de Andrade, & Valencia, 2005; Tisdall & Oades, 1982; Tivet, Sá, Lal, Briedis, et al., 2013). Therefore, soil aggregate stability indicates the ability of soil to sequester SOC and might be used as an indicator of sustainable soil management practices.

The frequent CT reduces the proportions of stable macroaggregates by breaking down soil aggregates (Zotarelli et al., 2007) and hastens SOC oxidation through stimulation of soil microbial biomass and activity (D. Guo et al., 2013; Six et al., 2004) thus resulting in high SOC humification degree (Balesdent, Chenu, & Balabane, 2000; Bayer et al., 2001; Six, Elliott, & Paustian, 2000) which reduces SOC storage (Bidisha, Joerg, & Yakov, 2010; Ogle et al., 2012). SOC sequestration in soils under NT systems is largely influenced by aggregation (Six et al., 2000). Soil aggregate stability is a function of the liberation of aggregating agents, principally by microorganisms, through the decomposition of organic residues (Cosentino, Chenu, & Le Bissonnais, 2006). NT has less deleterious effects on soil structure (Lal & Kimble, 1997) and provides the constant inputs of organic materials to generate a range of aggregating agents such as fungal hyphae, microbial bio-products (Haynes & Francis, 1993) and root exudates (Guggenberger et al., 1999). The improved soil aggregation through NT can enhance the physical protection of SOC against losses due either to mineralization or detachability and erosion (Feller & Beare, 1997). It has been widely observed that NT with crop rotations have significantly higher aggregate stability, a greater protection of SOC (Barreto et al., 2009; Castro Filho, Lourenço, de F. Guimarães, & Fonseca, 2002; Denef et al., 2004; Madari et al., 2005), and larger aggregates and larger proportion of the soil in greater aggregate size classes (Barreto et al., 2009; Madari et al., 2005; Tivet, Sá, Lal, Briedis, et al., 2013) compared with those of CT. Tivet, Sá, Lal, Briedis, et al. (2013) investigated the impacts of CT and NT on aggregate size distribution and aggregate-associated SOC in a red tropical Latosol. After eight years, the results indicated that the proportions of large macroaggregates (8-19 mm) decreased from 50% under NV to 35% under CT, and ranged from 33% to 51% under intensive NT cropping systems (high and diversified annual C inputs) in the 0-20 cm soil depth. Consequently, soil under CT had higher amounts meso- and microaggregates, indicating the disruptive effect of CT on aggregate size distribution. SOC stocks in the large macroaggregate fraction represented 52%, 37% and 41% of the total SOC stocks across all aggregate size under NV, CT and NT, respectively. The positive correlation between aggregate-associated SOC concentrations and labile SOC was also reported. It was concluded that NT with diverse biomass-C inputs increased SOC and reformed the largest macroaggregates that is crucial to SOC storage and stabilization. Similarly, Madari et al. (2005) studied the effects of NT and crop rotations on soil aggregation and SOC dynamics in a Rhodic Ferralsol in the subtropical climate. They found that the conversion of forest to cultivated land reduced the proportions of large macroaggregate (8-19 mm) by 70% and 32% at 0-5 cm depth under CT and NT, respectively. The aggregate-associated SOC under NT was greater than that under CT in the eight size classes in the top soil layer (0-5 cm). It was concluded that NT with crop rotations enhanced soil macro-aggregation and aggregate-associated SOC in the 0-5 cm soil depth due to the absence of soil disturbance and higher biomass-C inputs to aggregates through a slower macroaggregate turnover rate. An improvement of soil aggregate stability under NT with high biomass-C inputs protects the enzymatic and microbial attacks and significantly contributes to SOC stabilization in aggregates leading to long-term C sequestration (Balesdent et al., 2000).

In conclusion, the adoption of CA or its components contributes to the restoration of SOC and its fractions previously destroyed by CT through the continuous biomass-C inputs (i.e., plant roots, root exudates, aboveground residues) which maintain C flow in the soil and the absence of physical disruption. Consequently, soils under CA have greater aggregate satiability and favor the formation of macroaggregates leading to SOC stabilization within aggregates which potentially protects SOC within macroaggregate-occluded microaggregates in the soil profile.

CHAPTER 3

Short-term Conservation Agriculture Impacts on Total, Particulate and Mineral-associated Soil Organic Carbon in a Savanna Tropical Agro-ecosystem

Abstract

Conservation agriculture (CA) is an effective tool that is used to increase soil C sequestration and enhance soil quality and agronomic productivity. However, rigorous empirical evidence from Southeast Asia, particularly in the Cambodian agro-ecosystem, is still scarce. The aim of this study was to quantify the short-term (i.e., five year) impacts of soil management and cropping systems on soil organic C (SOC), soil total N (STN), particulate organic C (POC) and mineral-associated organic C (MAOC). There were three distinct experiments comprised of a combination of cover and main crops, including rice-, soybean- and cassava-based cropping systems, hereafter designated as RcCS, SbCS and CsCS, respectively. The experimental plots were laid out in a randomized complete block design with three replicates. Soil management treatments included conventional tillage (CT) and no-till (NT) and a selected adjacent area of the reference vegetation (RV). Soil sampling was conducted in 2011 and 2013 at seven depths (0-5, 5-10, 10-20, 20-40, 40-60, 60-80 and 80-100 cm). Soil management and crop sequences significantly affected SOC and STN stocks in all three cropping systems. On average, NT increased SOC stocks at 0-5 cm depth over those of CT by 10%, 20% and 18% and STN stocks by 8%, 25% and 16% for RcCS, SbCS and CsCS, respectively. SOC levels followed the order RV > NT >CT. SOC stocks in the subsoil layers were consistently in NT than in CT in all three cropping systems. POC stocks at 0-5 cm depth in NT were on average 22%, 20% and 78% greater than those in CT in RcCS, SbCS and CsCS, respectively. However, significant differences were detected only in RcCS and CsCS. The major POC stocks were found at 0-20

cm depth. NT treatments in SbCS stored 9% greater MAOC stocks at 0-5 cm depth than those in CT, and an increasing trend of NT was observed in RcCS and CsCS. In all three cropping systems, NT systems with diversified crop significantly affected SOC and POC stocks in the surface soils and tended to restore SOC and POC in the subsoil layers after five years. The results agree with the observation that short-term CA associated with high biomass-C inputs (particularly bi-annual rotations) promotes SOC recovery in the topsoil layer and creates a potential to increase SOC in the subsoil layers when deep-rooting cover crops are included in crop rotations.

3.1 Introduction

Agricultural land expansion for crop production, due to rural population growth, has gradually diminished forest area and exacerbated the growing concern over soil degradation in Cambodia (Belfield et al., 2013; Hean, 2004; Poffenberger, 2009; UNDP, 2010). The development of annual upland crops (i.e., maize, cassava, soybean and mung bean) soared from 217,106 ha in 2003 to 716,370 ha in 2012 (MAFF, 2013). Currently, their production has become an important component of smallholder agriculture development in the western and northern regions of the country, although negative impacts on natural resources and farm economy are already noticeable. Most soil types identified have a rather low natural fertility, and the process of soil degradation is apparent in most parts of the country (Johnsen & Munford, 2012). Soil degradation reduces the productivity of arable land and poses a serious threat to sustained agricultural productivity and food security (CDRI, 2014; UNDP, 2010). Over 40% of the Cambodian population is affected by land degradation, which represents 78,000 km^2 or 43% of total land area (Bai et al., 2008). Despite substantial growth of various sectors, Cambodia’s economy is still predominantly agrarian. The agricultural sector contributed close one-third of

Cambodia's GDP in recent years and employed more than half of the country's total labor force (Yu & Diao, 2011). Thus, the country is faced with a challenge to sustainably increase crop productivity while conserving soil quality and protecting the environment. Continuous conventional plow-based tillage practices and crop residue removal from agricultural land have been implemented for decades and have negative effects on soil productivity and sustainability (Farooq et al., 2011; Franzluebbers, 2008; Govaerts et al., 2009). These practices cause increased decomposition of previously stable soil organic matter (SOM) due to physical soil disruption and greater exposure of young and stable C to microbial attack (Reicosky et al., 1995; Sá et al., 2013). Land use and agricultural management practices such as tillage, mulching and crop residue management influence soil organic carbon (SOC) dynamics (Chivenge et al., 2007; Lal, 1997; Six et al., 2002). SOC plays a crucial role in sustaining soil quality and crop productivity (Lal, 2006; Reeves, 1997) due to its profound influence on soil properties (Brévault et al., 2007; Lienhard et al., 2013; Sá et al., 2009; Tisdall & Oades, 1982). A decline in SOC due to the conversion of natural forest or native vegetation into cropland is a common phenomenon (Lal, 2002). This decline results from a reduction in total organic C inputs and an increase in decomposition rate (Shibu et al., 2010; Tivet, Sá, Lal, Borszowskei, et al., 2013). Sá et al. (2013) report that SOC stock of 0.67 Mg C ha^{-1} $year^{-1}$ at a 0-20 cm depth was depleted after eight years of conversion from native vegetation to agricultural land using a continuous plow-based tillage in a tropical region (i.e., Cerrado) of Brazil.

SOC dynamics under conservation agriculture (CA) systems are driven by the balance of C inputs (via crop residues) and C outputs (via microbial oxidation) (Davidson & Janssens, 2006; Lal, 2004b; Powlson et al., 1987). NT cropping systems based on high diversity and biomass-C inputs, which utilize more of the available growing periods may offer a potential approach to restore SOC by maximizing below- and aboveground C inputs. CA has been practiced since the 1960's and has spread widely (Friedrich et al., 2012). CA utilizes the basic tools to create sustainable agriculture based on its three key principles: (i) minimum soil disturbance (no-till) restricted to sowing rows, (ii) permanent soil cover by organic mulch, and (iii) crop species diversification (FAO, 2008). This set of improved management practices aims to enhance soil quality, restore SOC and increase crop productivity (Díaz-Zorita et al., 1999; Farooq et al., 2011; Govaerts et al., 2009; Sá et al., 2014). SOC accumulation under NT responds to soil properties (Batlle-Bayer et al., 2010) and the overall amount, quality and frequency of crop biomass inputs to soils (Batlle-Bayer et al., 2010; Ogle et al., 2012; Virto et al., 2012).

Some physical fractions of SOM are more sensitive to soil management and can be good indicators of soil management changes over a short-time period (Dou, Wright, & Hons, 2008). Physical fractionation is a useful tool to interpret SOC dynamics by providing a rough differentiation between active, intermediate and passive SOC pools. Physical fractionation may also be used to assess the impact of soil management on dynamics (Cambardella & Elliott, 1994; Christensen, 1992; Six et al., 1999) and quantitative changes (Bayer et al., 2000) in SOC. Particle-size fractionation of soil plays an important role in assessing the SOM accessibility (Gregorich et al., 2006) and interactions between organic and inorganic soil components in the turnover of SOM (Christensen, 1992, 2001). Particulate organic C (POC), a labile fraction, is a sensitive pool of organic C and therefore considered a good qualitative indicator with which to detect changes in SOM due to land use and management (Cambardella & Elliott, 1992; Freixo et al., 2002). Changes in POC are directly related to the quantity, quality and frequency of crop residues added to soil (Diekow et al., 2005; Lienhard et al., 2013; Sá et al., 2001; Vieira et al., 2007). Mineral-associated organic C (MAOC) is considered a stable fraction and is less sensitive than POC to land use and management. It reflects the relationship between SOC and the silt- and clay-size fractions (Bayer et al., 2001; Sá et al., 2001). MAOC can be changed by physical and chemical soil environment rather than by land use changes (Guggenberger et al., 1994), resulting in a lower turnover rate (Feller & Beare, 1997). The results reported by Tivet, Sá, Lal, Borszowskei, et al. (2013) indicate that the conversion of native vegetation to cultivated land under CT reduced POC and MAOC pools, with estimated losses of 71% and 40%, respectively, at 0-5 cm soil depth in a tropical red Latosol.

In Cambodia, some studies on SOC dynamics have been conducted in the forest soils (Khun, Lee, Hyun, Park, & Combalicer, 2012; Kiyono et al., 2010; Sasaki, 2006; Toriyama et al., 2012; Toriyama et al., 2011), but there is still a paucity of information on the effects of soil management practices on SOC dynamics in cropland soils. Although it seems obvious that long-term CA can be an effective agricultural practice for increasing SOC, its short-term impacts on SOC dynamics are often variable and not well-documented. The hypothesis of this study was based on the idea that high and diversified biomass-C inputs in CA might be the first step toward increasing SOC in the topsoil by creating the C flow to support C storage. Therefore, this study was carried out to assess the short-term (i.e., five year) responses of SOC, STN, POC and MAOC fractions in a Cambodian Oxisol to tillage and cropping systems with diverse biomass-C inputs under NT management.

3.2 Materials and Methods

3.2.1 Site description. The experimental site was located in Chamkar Leu District, Kampong Cham Province, Cambodia (latitude 12°12′30″N, longitude 105°19′7″E, 118 m elevation; see Figure 3.1). In 1937, the natural forest at this location was converted to agricultural land, and crops (including cashew, coffee, mango, mulberry, avocado and rubber) were planted soon after forest clearance. Between 1970 and 1982, the area was abandoned, and *Tetrameles nudiflora, Nauclea officinalis, Cassia siamea* and *Leucaena glauca* grew naturally. Cotton (*Gossypium hirsutum* L.) and banana (*Musa spp.*) were widely planted from 1982 to 2000. From 2000 to 2009, two crops per year, including cotton, mung bean (*Vigna radiata* (L.) R. Wilczek), maize (*Zea mays* L.), sesame (*Sesamum indicum* L.) and soybean (*Glycine max* (L.) Merr.) were rotated under CT before the start of this experiment. Mineral fertilizers such NPK 15-15-15 fertilizer, ammonium phosphate (16-20-0) and potassium chloride (0-0-60) were applied without lime application (see Figure 3.2b). The soil of the study site is a red Latosol (equivalent to Oxisols in USDA-Soil Taxonomy or Ferralsols in FAO-Soil Classification) (Crocker, 1962; Kubota, 2005). Due to forest conversion to rubber plantation in the 1960s in the areas surrounding the experimental plots, soil samples could not be obtained from the native forest and vegetation as a reference site. An adjacent reference vegetation (RV) site (latitude 12°12′13″N, longitude 105°19′11″E and 118 m asl) located approximately 500 m from the experimental plots was selected as a baseline to assess the management-induced changes in SOC and its fractions in this study. The vegetation composition of RV was an old coffee plantation under the shade of *Leucaena glauca* that was planted in 1990. The crop history here was the same as that of the experimental plots from 1937 to 1990 after conversion of natural forest to cultivated land (Figure 3.2a). The research site has a tropical monsoon climate with two distinct seasons, rainy (May-October) and dry (November-April). The mean annual temperature was 28 ºC and the mean annual maximum and minimum temperatures were 32 ºC and 24 ºC, respectively. The mean annual precipitation (2009–2013) in the experimental site was 1716 mm distributed mainly over the six months of the rainy season.

3.2.2 Experimental design and treatment description. The experiments were initiated in 2009 by the Conservation Agriculture Service Centre (CASC), General Directorate of Agriculture of Cambodia in collaboration with Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), France. Three experiments were conducted as part of this study, including (a) rice-, (b) soybean-, and (c) cassava-based cropping systems (RcCS, SbCS and CsCS, respectively). The experimental plots of each cropping system were laid out in a randomized complete block design with three replicates. Plot dimensions were 8 m × 37.5 m. Each cropping system was comprised of four treatments: (a) conventional tillage (CT) system with disc plowing to a 15- to 20-cm depth, in which the main crops (i.e., rice and soybean) were planted in annual succession for rice and soybean (i.e., mung bean/rice, –CT-Rc, sesame/soybean, –CT-Sb) and mono-cropped for cassava (–CT-Cs); (b) NT systems in which the main crops (rice, soybean, and cassava) were grown in a one-year frequency pattern (NT1-Rc, NT1-Sb, NT1-Cs); and (c) and (d) NT systems in which the main crops were grown in bi-annual rotations with maize; the two plots in these bi-annual rotations were NT2-Rc, NT3-Rc for rice, NT2-Sb, NT3-Sb for soybean and NT2-Cs, NT3-Cs for cassava. The details of main and cover crop successions are presented in Table 3.1. In NT1, NT2 and NT3, stylo (*Stylosanthes guianensis*) was used as a cover crop and grown in association with the main crops. This cover crop was sown in the middle of the inter-row at 0, 15, and 35 days after the sowing of maize, cassava, and rice, respectively, and by seed broadcasting at the beginning of soybean maturation, approximately 30 days before harvest. Congo grass (*Brachiaria ruziziensis*) was used once in 2009 under NT1-Sb and NT3-Sb (Table 3.1). In addition, if the development and/or density of the cover crops sown the previous year were considered insufficient, millet (*Pennisetum typhoides*) or sorghum (*Sorghum bicolor*) was sown alone or in alternate lines with sunhemp

(*Crotalaria juncea*) at the beginning of the rainy season. The cover crops were then grown for 60 to 75 days to strengthen the biomass inputs prior to the main cycle of rice, soybean or maize. CT was operated prior to each crop with a 7-disc plow pulled by an 80-horse-power tractor. Main and cover crops (at the beginning of the rainy season) were sown with a 2-rows no-till planter (Fitarelli) drawn by a 12-horse-power hand-tractor. Sesame, mung bean and associated cover crops were sown manually. Fertilizers were applied under the form of basal application with thermo phosphate (i.e., 16% P_2O_5, 31% CaO and 16% MgO), and fractioned top dressing on main crops with nitrogen and potassium, using urea (46 % N) and potassium chloride (60 % K_2O), respectively, as described in Table 3.2.

3.2.3 Total dry biomass and above- and below ground C inputs. Five sub-plots (10 m × 2.4 m for rice, soybean and maize; 2.5 m ×1.6 m for sunhemp, millet, stylo, sorghum and Congo grass; 2 m × 2 m for mung bean and sesame; 1 m × 2 m for cassava leaves) and three sub-plots (4 m × 5 m for cassava stems) were collected on each plot to measure the aboveground biomass input. Fresh residues were weighed and 2 kilograms of crop residues were then chopped and dried at 70 ºC to a constant weight. The moisture content was calculated and the total dry biomass was converted based on the moisture content of each crop. The belowground biomass-C inputs from crop residues were estimated by multiplying the root to shoot (RS) ratio by the aboveground biomass of each crop (Sá et al., 2001; Sá et al., 2013; Sá et al., 2014). Belowground biomass of cassava was not estimated. The RS ratios were 0.25 for rice, 0.24 for maize, 0.27 for soybean, 0.27 for millet, 0.26 for sunhemp, 0.38 for Congo grass, 0.30 for sorghum, 0.30 for mung bean, 0.35 for sesame and 0.33 for stylo. The C concentration (g kg^{-1} of dry matter) in crop residues was 459 for rice, 455 for maize, 375 for mungbean, 395 for soybean, 385 for sesame, 448 for cassava, 428 for millet, 440 for sunhemp, 443 for Congo grass, 444 for sorghum, and 410 for stylo. Details of cumulative and annual C inputs are presented in Table 3.1.

3.2.4 Soil sampling and processing. Soil samples were taken in November 2011 and 2013. Composite soil samples were collected from each treatment at seven depths: 0-5, 5-10, 10-20, 20-40, 40-60, 60-80, and 80-100 cm. Bulk soil samples were obtained for the 0-5, 5-10 and 10-20 cm depths by digging 20 × 20 cm trenches and for the 20-40, 40-60, 60-80 and 80-100 cm depths with an auger (4.5-cm diameter). Soil samples collected from six randomly selected points within each plot were composited. Bulk soil samples were oven-dried at 40 ºC, gently ground, sieved through a 2-mm sieve and homogenized. Visible pieces of organic materials were removed. Similarly, six subplots were demarcated for soil sampling in an approximately 17 ha area in the adjacent reference vegetation (RV) in 2011 which were used as a baseline for comparison with the three cropping systems. Bulk soil samples were collected randomly from six different points at each depth per subplot and composited. In 2011, soil bulk density (ρ_b) for each depth was sampled by opening two pits (70 cm × 70 cm) per experimental plot and assessed by the core method (Blake & Hartge, 1986) using cores of 5 cm in diameter and 5 cm high. A soil core was obtained in the middle of each of the following depths: 10-20, 20-40, 40-60, 60-80 and 80-100 cm. Two cores were collected for each depth per pit, and soil cores were oven-dried at 105 ºC. Because the soil was heavy-clay, it was assumed that the bulk density had not changed within two years. Thus, the bulk density was measured only in 2011 and also used to calculate C, N and POC stocks in 2013.

3.2.5 Soil analysis.

3.2.5.1 Soil chemical and mineralogical properties and particle-size distribution analyses. The analysis of soil properties was conducted with soil samples collected in 2011 after the third year of the experiment. Soil pH was determined at soil:$CaCl_2$ ratio 1:2.5, and exchangeable Al^{3+}, Ca^{2+}, Mg^{2+} were extracted with 1 mol L^{-1} KCl and K^+ with Mehlich-1 solution. Al^{3+} was determined by titration with 0.025 mol L^{-1} NaOH, Ca^{2+} and Mg^{2+} were determined by titration with 0.025 mol L^{-1} EDTA. K^+ was determined by flame photometry. All soil fertility attributes were performed following the procedures described by Pavan, Bloch, Zempulski, Miyazawa, and Zocoler (1992). Soil samples passed through 20 µm from the RV and experimental sites at depths of 0-20, 20-40 and 60-100 cm were used to identify clay minerals by X-ray diffraction technique (Jackson, 1966) using Ultima IV X-ray Diffractometer (RIGAKU, Japan). The X-ray diffractogram pointed out that the major dominant clay mineral in the soils at both sites was kaolinite. Particle-size distributions for all depths were determined by a modified version of the standard Bouyoucos hydrometer method without removal of carbonates and organic matter (Gee & Bauder, 1986). The results of soil attributes are shown in Table 3.3.

3.2.5.2 Total soil organic C and N concentrations in bulk soils and stock calculation. Sub-samples of 2-mm sieved bulk soils were finely ground (<150 µm), and then analyzed for total C and N concentrations by the dry combustion method using an elemental CN analyzer (TruSpec CN, LECO, St. Joseph, USA). The SOC stocks were calculated using the expression: SOC stock = (TOC × ρ_b × *th*)/10, in which SOC stock is the stock of total organic C at a specific depth (Mg ha^{-1}), TOC is the concentration of total organic C (g kg^{-1}), ρ_b is the bulk density (Mg m^{-3}), and *th* is the thickness of each soil depth (cm). Due to the significant differences in bulk density between RV and treated soils (presented in Table 3.4), SOC stocks were calculated for all depths and computed on an equivalent soil mass-depth basis as described by Ellert and Bettany (1995).

3.2.5.3 Particle-size fractionation of soil organic C. SOC was physically fractionated using the bulk samples. The particle-size fractionation was performed using a method adapted from Sá et al. (2001). Briefly, a 40 g soil sample was dispersed with a solution of 1.25 g sodium hexametaphosphate and 100 mL deionized water and stored for 16 h at approximately 10 ºC. Then, the sample was horizontally shaken at 100 rpm with three 10-mm diameter agate balls for 8 h. The soil suspension was wet-sieved through a 53-µm sieve with deionized to obtain the fraction between 53 µm and 2000 µm in size, which represented particulate organic C (POC). The ≤ 53 µm fraction was transferred to a 1-L glass cylinder and flocculated with 2-g $CaCl_2$. After complete sedimentation, the supernatant was siphoned. This ≤ 53 µm fraction represents mineral-associated organic C (MAOC). The two fractions were oven-dried at 40-ºC and finely ground, and total C was determined using an elemental CN analyzer (as describe above). The POC and MAOC stocks were computed on an equivalent soil mass-depth basis.

3.2.6 Statistical analysis. Statistical analysis of all data was performed using SAS 9.2 statistical software. To compare the effects of tillage and crop rotation treatments at each depth in each cropping system, data were subjected to analysis of variance procedures with randomized complete block design. Comparisons among treatment means were calculated based on least significant difference (LSD) tests at the 0.05 probability level, unless otherwise stated.

3.3 Results

3.3.1 Soil organic C (SOC) and soil total N (STN).

***3.3.1.1 Rice-based cropping systems*.** No significant increase in SOC concentrations under the three NT treatments were observed when compared to CT-Rc in all soil depths (Figure 3.3). The SOC concentrations under CT-Rc and NT-Rc (average of NT1-Rc, NT2-Rc and NT3-Rc) were 19.68 g kg^{-1} and 19.15 g kg^{-1}, respectively, at the 0-5 cm depth in 2011. Although higher SOC concentration was found in CT-Rc soil at 0-5 cm depth in 2011, NT-Rc soils accumulated an average of 10% more SOC in 2013 compared with CT-Rc. At deeper soil layers, there were no noticeable differences between CT-Rc and NT-Rc soils. It was observed that SOC concentrations decreased with increasing soil depth. Similar to SOC, results of STN concentrations showed no significant differences between CT-Rc and three NT-Rc treatments (Figure 3.3). NT-Rc soils had a higher STN concentration than that of CT-Rc, ranging from 3% to 8% in 2011, and 6% to 10% 2013 at 0-5 cm depth. The bi-annual crop rotation treatments (NT2-Rc and NT3-Rc) also showed an increased accumulation of STN, with 7% in 2011 and 10% in 2013 at 5-10 cm depth.

Differences in tillage and crop rotation treatments did not show a significant effect on SOC and STN stocks at any depth (Table 3.5 & 3.6). NT-Rc soils (average of NT1-Rc, NT2-Rc and NT3-Rc) stored 3% less SOC stock than that of CT-Rc soil at 0-5 cm depth in 2011. However, NT-Rc had 10% more SOC stock than that of CT-Rc in the surface layer in 2013. NT-Rc showed an increase in 0.8 Mg ha^{-1} for SOC, and 0.05 Mg ha^{-1} for STN at 0-5 cm depth in 2011 compared with the initial stocks in 2009. SOC and STN stocks under RV were significantly higher than those under CT-Rc and NT-Rc at 0-5 and 5-10 cm depths ($P<0.001$ and $P<0.01$, respectively). In 2011, SOC stock under RV was 58% and 63% significantly greater than those under CT-Rc and NT-Rc, respectively, at 0-5 cm. However, NT-Rc soils tended to sequester more SOC compared with that of CT-Rc in 2013, when the percentage of SOC stock under RV was 46% and 33% greater than those under CT-Rc and NT-Rc soils, respectively. Considering the 100 cm as a single stratum, no differences were found among treatments for SOC reserves in either 2011 or 2013, or for STN reserves in 2011. The changes in sequestration rates of NT-Rc treatments were twice as high (average rate of 5.77 Mg C ha^{-1} yr^{-1}) as that of CT-Rc soil (2.95

Mg C ha^{-1} yr^{-1}). In contrast, STN reserves decreased in all treatments by rates of 0.16 and 0.83 Mg C ha^{-1} yr^{-1} under CT-Rc and NT-Rc soils, respectively.

3.3.1.2 Soybean-based cropping systems. SOC concentrations significantly increased ($P<0.05$) in the 0-5 cm depth in response to tillage and crop rotation treatments in both 2011 and 2013 (Figure 3.4). The SOC concentrations of soils under NT2-Sb and NT3-Sb (bi-annual crop rotations) were 8% and 4% greater, respectively, than that under CT-Sb in 2011. CT-Sb soil showed a 5% increase in SOC concentration in 2013. However, NT-Sb soils contained significantly more 20% SOC than that of CT-Sb. NT soils accumulated more SOC when compared with the percentage of SOC sequestered by NT-Sb from 2011 to 2013. SOC concentrations under NT1-Sb, NT2-Sb and NT3-Sb increased 21%, 13%, and 23%, respectively. RV soil contained greater SOC concentrations (61% and 53% at 0-5 cm depth and 14% and 23% at 5-10 cm depth) than CT-Sb and NT-Sb soils, respectively, in 2011. SOC results in 2013 showed an increase in both CT-Sb and NT-Sb soils. However, NT-Sb soils still maintained higher accumulated SOC than that of CT-Sb (based on their differences from RV soil) as they decreased from 53% to 28% at 0-5 cm and 23% to 17% at 5-10 cm, whereas these values under CT-Sb decreased from 61% to 53% at 0-5 cm and 14.4% to 14.2% at 5-10 cm. STN sampled in 2011 did not differ among tillage and crop rotation treatments, but effects were detected in 2013 at 0-5, 5-10, 20-40 and 60-80 cm depths (Figure 3.4). STN concentrations were greater in NT-Sb soils, particularly NT2-Sb and NT3-Sb. RV soil contained 74% and 66% at 0-5 cm and 35% and 30% at 5-10 cm STN concentrations that were higher than those of CT-Sb and NT-Sb soils, respectively, in 2011. When comparing changes from 2011 to 2013, STN concentrations decreased 12% and 18% under CT-Sb but increased 5% and 3% under NT-Sb at 0-5 and 5-10 cm depths, respectively.

SOC stocks were higher by 6% in 2011 and 20% in 2013 under bi-annual rotation treatments (NT2-Sb and NT3-Sb) when compared with those of CT-Sb (Table 3.7). SOC stock under NT1-Sb did not differ from that of CT-Sb in 2011, but a significant difference was detected in 2013, in which NT1-Sb stored 20% greater SOC stock. An increase of SOC in subsoil layers was observed in both NT-Sb and CT-Sb. SOC stocks under RV soils were significantly higher than those under CT-Sb and NT-Sb at 0-5 cm and 5-10 cm depths in 2011 and 2013. The SOC stock under NT-Sb (average of NT1-Sb, NT2-Sb and NT3-Sb) at 0-5 cm depth was 53% lower than that under RV in 2011. It decreased to 28% in 2013 and decreased from 61% to 53% in CT-Sb soil. When comparing with RV, it was evident that SOC stocks decreased in the order RV > NT > CT only at 0-5 cm soil depth in 2011 and 2013. From 2011 to 2013, changes in the SOC reserves at 100 cm depth (as a single stratum) indicated an increasing trend of NT-Sb over CT-Sb. Soils under NT1-Sb, NT2-Sb and NT3-Sb sequestered 1.75, 2.45, and 2.85 Mg C ha^{-1} yr^{-1}, respectively. STN stocks were not affected by tillage and crop rotation treatments in 2011 but significant differences between CT-Sb and NT-Sb were observed at 0-5 and 5-10 cm depths ($P<0.01$ and $P<0.05$, respectively) in 2013 (Table 3.8). In 2013, an increase of 0.21 Mg N ha^{-1} was recorded in NT-Sb soils at 0-5 cm and 5-10 cm depths. Considering the 100 cm depth to be as a single stratum, average STN stocks under NT2-Sb and NT3-Sb stored 55% greater than under CT-Sb. Although 29% more STN stock was found in NT1-Sb, this treatment did not significantly differ from CT-Sb.

3.3.1.3 Cassava-based cropping systems. Similar to SbCS, tillage and crop rotation treatments affected the SOC concentrations only at the 0-5 cm layer ($P<0.05$) in both 2011 and 2013. Significant changes ($P<0.01$) in STN concentrations were observed at 0-5 and 5-10 cm depths in 2013 (Figure 3.5). On average, the bi-annual crop rotation treatments (NT2-Cs and

NT3-Cs) experienced an increase in SOC concentration of 17% in 2011 and 22% in 2013 over that of CT-Cs. NT1-Cs did not differ in SOC concentration when compared with CT-Cs. Although they were not significantly different, NT1-Cs accumulated 11% more SOC in 2013. Similarly, STN concentration in NT3-Cs was 21% higher than that of CT-Cs in 2011 and 31% higher in 2013 at 0-5 cm depth (Figure 3.5). STN concentrations under the other two NT treatments (NT1-Cs and NT2-Cs) were higher but not significantly different from those under CT-Cs at 0-5 cm depth in 2013.

Differences in tillage and crop rotations resulted in significant differences in SOC stocks at 0-5 cm depth in 2011 ($P<0.05$) and 2013 ($P<0.01$) (Table 3.9), and STN stocks ($P<0.01$) at 0-5 and 5-10 cm depths in 2013 (Table 3.10). Soils under NT2-Cs and NT3-Cs stored 15% and 19% higher SOC stocks in 2011 and 16% and 28% in 2013, respectively, than under CT-Cs at 0-5 cm depth. In 2013, SOC stock was greater under NT1-Cs than under CT-Cs, but not significantly so. SOC stocks under CT-Cs, NT1-Cs, NT2-Cs and NT3-Cs were 99%, 99%, 72% and 67% lower, respectively, than under RV at 0-5 cm depth in 2011. SOC stocks increased in 2013 and the differences with RV dropped to 78%, 60%, 53% and 40% under CT-Cs, NT1-Cs, NT2-Cs and NT3-Cs, respectively. Changes in the SOC reserves at 0-100 cm depth from 2011 to 2013 indicated that NT-Cs produced greater values than CT-Cs; soils under NT1-Cs, NT2-Cs and NT3-Cs sequestered 2.80, 2.35 and 3.30 Mg C ha^{-1} yr^{-1}, respectively, more than CT-Cs soil. There were no noticeable changes in STN stocks at any depth from 2011 to 2013. However, NT2-Cs and NT3-Cs stored 13% and 31% significantly greater STN stocks, respectively, when compared with CT-Cs at 0-5 cm depth as well as 23% greater under NT3-Cs at 5-10 cm in 2013.

3.3.2 Particulate and mineral-associated organic C (POC and MAOC).

3.3.2.1 Rice-based cropping systems. The adoption of NT crop rotations significantly ($P < 0.05$) increased POC concentrations at 0-5 cm depth in 2013 (Figure 3.6b). Soil under NT3-Rc accumulated 35% greater POC than under CT-Rc. NT1-Rc and NT2-Rc did not differ from CT-Rc but an increasing trend of 16% and 15% more POC than CT-Rc under NT1-Rc and NT2-Rc, respectively, was observed. No significant differences in POC and MAOC concentrations were observed in 2011 at any depth except 80–100 cm for MAOC (Figure 3.6a). The POC concentrations in the two highest soil layers noticeably increased in all treatments from 2011 to 2013. This increase was also observed at deeper soil depths. When comparing treatments, MAOC concentrations were nearly constant at all depths, except soils at80-100 cm at which CT-Rc and NT2-Rc soils contained the highest MAOC concentrations. Silt plus clay-associated C, averaged across all soil depths, represented 88%, 84%, 92%, 89% and 86% of TOC under RV, CT-Rc, NT1-Rc, NT2-Rc and NT3-Rc, respectively.

POC stocks and MAOC stock in 2011 were not influenced by treatments, except for MAOC stock at 80-100 cm depth. However, POC stocks under NT-Rc significantly ($P<0.05$) increased at 0-5 cm depth compared with those of CT-Rc in 2013 (Tables 3.11 and 3.12). Compared with POC stocks in 2011, the increased rates in 2013 ranged from 0.43 to 0.68 Mg ha^{-1} at 0-5 cm depth. When comparing with RV, POC stocks under treated soils were significantly lower at 0-5, 20-40 and 40-60 cm depths in 2011 but differed only at 0-5 cm depth in 2013. Similarly, significantly greater MAOC stocks under RV than those under CT-Rc and NT-Rc were detected at 0-5 and 5-10 cm depths in 2011. RV soil on average had 37% and 35% higher MAOC stocks at 0-5 cm and 22% and 23% higher MAOC stocks at 5-10 cm than CT-Rc and NT-Rc soils, respectively. Considering the 100 cm as a single stratum, RV soil had greater POC and MAOC stocks than the treated soils in 2011 but greater POC stocks under RV were not apparent in 2013. The POC stocks at 0-20 cm depth were 66% (for RV), 71% (CT-Rc, NT1-Rc and NT2-Rc), and 72% (NT3-Rc) of the total POC stocks in 0-100 cm.

3.3.2.2 Soybean-based cropping systems. Tillage and crop rotation treatments did not significantly affect POC concentrations in any soil layers in either 2011 or 2013, with the exception of POC at 40-60 cm and MAOC at 0-5 cm and 40-60 cm depths in 2011 (Figure 3.7). Although they did not differ in the surface layer, NT treatments on average had 20% greater POC concentration than that of CT-Sb at 0-5 cm depth in 2013. POC concentrations in all treatments increased in 2013 compared with those in 2011 and POC concentration was greater (though not significantly so) NT-Sb compared with CT-Sb. MAOC concentrations were greater in all NT-Sb treatments in the soil surface. Soils under NT1-Sb, NT2-Sb and NT3-Sb had 6%, 12% and 8% higher MAOC concentrations, respectively, than those under CT-Sb. Similar to RcCS, silt plus clay-associated C was the dominant proportion of the fractions. Averaged across all soil depths, it represented 87%, 90%, 90% and 89% of SOC concentrations under CT-Sb, NT1-Sb, NT2-Sb, and NT3-Sb, respectively.

Significant effects of tillage and crop rotations on POC stocks were not detected, with the exception of those at 40-60 and 80-100 cm depths (Table 3.13). Greater MAOC stocks in soils under NT-Sb compared with those under CT-Sb occurred at 0-5 and 40-60 cm depths in 2011 (Table 3.14). POC stocks under NT-Sb soils tended to be higher (but not significantly so) than under CT-Sb soils. In 2013, CT-Sb, NT1-Sb, NT2-Sb and NT3-Sb practices increased POC stocks by 65%, 100%, 70%, and 73%, respectively, when compared with POC stocks in 2011 at 0-5 cm depth. A slight increase was also observed in the subsoil layers. However, the major POC stocks were found in the 0-20 cm depth where they represented 68% (CT-Sb), 65% (NT1-Sb), 70% (NT2-Sb) and 71% (NT3-Sb). In 2011, RV soils contained 146% and 123% significantly higher POC stocks at 0-5 cm depth, and 56% and 70% significantly POC stocks at 5-10 cm depth than those at CT-Sb and NT-Sb soils, respectively. However, these values did not differ in 2013. Considering the 100 cm as a single stratum, POC stocks under NT-Sb increased (but not significantly so) when compared with those under CT-Sb. From 2011 to 2013, NT1-Sb, NT2-Sb, and NT3-Sb were greater by 0.16, 0.35, and 0.33 Mg C ha^{-1}, respectively, than that of CT-Sb. When compared with RV, POC stocks of treated soils were significantly lower at most depths in 2011 but not significantly different in 2013. In contrast to POC stocks, soils under NT1-Sb, NT2-Sb and NT3-Sb had 6%, 12% and 8% significantly higher MAOC stocks, respectively, than soils under CT-Sb at 0-5 cm depth in 2011. When compared with RV, MAOC stocks under RV were 55% and 43% significantly higher than that of CT-Sb and NT-Sb soils at 0-5 cm. The significantly lower stock was also detected at 5-10 cm (Table 3.14). MAOC accounted for 80% of SOC stock under cultivated fields (CT-Sb and NT-Sb) and 86% under RV (100 cm considered a single stratum).

3.3.2.3 Cassava-based cropping systems. POC concentrations at 0-5 cm depth were influenced by tillage and crop rotation treatments after five years ($P < 0.01$). Although they did not significantly differ in 2011, bi-annual rotation treatments (NT2-Cs and NT3-Cs) tended to be greater than CT-Cs. (Figure 3.8a). From 2011 to 2013, POC concentrations increased in all treatments, but the greatest increase was found in the 0-20 cm depth. In contrast, MAOC concentrations were not affected by the treatments (Figure 3.8b). The proportion of MAOC remained constant. The silt plus clay-associated C, averaged across all soil depths, represented 89% of the SOC concentrations in cultivated fields (CT-Cs and NT-Cs).

Significant differences in POC and MAOC stocks were not detected in 2011, but the adoption of NT significantly ($P < 0.01$) increased POC stocks at the 0-5 cm depth in 2013 (Tables 3.15 and 3.16). NT2-Cs and NT3-Cs had 56% and 127% greater POC stocks, respectively, than that of CT-Cs. After five years under the same NT systems, NT2-Cs and NT3-Cs were more likely to have increased POC stocks compared with NT1-Cs after five years. The POC stocks in the 0-10 cm depth represented 1.2, 1.3 and 1.6 times more C under NT1-Cs, NT2-Cs, and NT3-Cs, respectively, than under CT-Cs after five years of NT practices. Although MAOC stocks did not differ among treatments, bi-annual rotations under NT systems (NT2-Cs and NT3-Cs) on average had a 7% increase in MAOC stocks than under CT-Cs. RV soil had the highest POC stock at 0-5 cm depth in both 2011 and 2013. However, NT systems tended to restore POC stocks nearly to the level under NT (particularly NT3-Cs). On average, MAOC stocks under RV were greater than those under CT-Cs and NT-Cs by 75% and 67% at 0-5 cm and 30% and 32% at 5-10 cm, respectively. Considering 100 cm as a single stratum, no significant differences in MAOC stocks between RV and cultivated fields (CT-Cs and NT-Cs) were apparent in 2011.

3.4 Discussion

3.4.1 Changes in Soil organic C and soil total N. Short-term (≤ 10 years) effects of agricultural management practices on SOC vary with soil conditions, climate, biomass-C return and the management itself (Al-Kaisi, Yin, & Licht, 2005). NT cropping system practices result in SOC increase in tropical soils compared with CT systems (Bayer, Martin-Neto, et al., 2006; Neto et al., 2010). The types of crop rotations and NT management practices produce significant changes in SOC sequestration due to an increase in biomass-C inputs returned to the soil and a decrease in soil disturbance. Sá et al. (2013) reported that NT cropping rotations with high C input cover crops maintain a permanent soil cover and support a continuous flow of biomass that releases organic compounds. However, the rate of SOC in short-term NT cropping systems with cover crops might be detected in the surface soil layer. In the present study, the bi-annual crop rotation treatments in SbCS and CsCS (NT2-Sb, NT3-Sb, NT2-Cs and NT3-Cs) increased in the surface soil layer after five years. In a tropical Oxisol in Laos, Lienhard et al. (2013) found an increase in SOC of approximately 15% at a soil depth of 0-10 cm under NT cropping system practices associated with diverse cover crops when compared with CT after two years. Over a five-year period in a semi-arid tropical climate, Scopel et al. (2005) found that soil C levels in mulch increased by 23 to 29% when compared with those of CT, mainly due to increased crop residue inputs and reduced soil C erosion in mulch treatments. Sá et al. (2013) also observed a significant change in SOC over eight-year NT cropping systems in association with Congo grass, sorghum and millet in a Brazilian Oxisol. This type of short-term effect was reported by McCarty, Lyssenko, and Starr (1998) in a temperate climate. They found a substantial increase of SOC (38%) in the 0-2.5 cm soil layer in NT soil after the first three years of tillage transition from plow tillage to NT. This increase in SOC in the surface soil could be related to the fact that in NT cropping systems with cover crops, soil was undisturbed and higher biomass-C was added, which create a positive C budget and accentuated C transformation and flow (Boddey et al., 2010; Sá et al., 2013). This finding also supports the hypothesis that a greater SOC accumulation over the short-term in NT cropping systems is found only in the top soil, when compared with that of CT. SOC accumulation in the soil surface is essential for identification of C restoration in response to biomass-C inputs and absence of physical disruption. The longer-term NT effects on SOC accumulation are apparent, but, empirical evidence in deeper layers of the soil profile is still scant due to the continuous biomass-C inputs. Sá et al. (2013) found a strong linear relationship between annual C input and annual SOC sequestration to soil depth of 1-m when deeply rooted cover and main crops were planted under eight years in NT systems in an Oxisol from humid tropic environment.

SOC sequestration is controlled by variability in the quantity and quality of biomass-C inputs (Ogle et al., 2005) and is increased with higher crop residue inputs and cropping intensity (Franzluebbers, Hons, & Zuberer, 1998). The soil from annual frequency pattern of soybeans (NT1-Sb) with various cover crops such as Congo grass, millet, stylo and sorghum have an increase in SOC after five years when compared with CT soil, but not NT1-Cs. The possible explanation could be that cassava was associated only with stylo, resulting in lower biomass-C inputs than other NT cropping sequences in CsCS. The higher N input obtained from stylo biomass under NT1-Cs than from that under CT-Cs could be associated with easily decomposable residues of cassava that result in more C oxidation than C converted to SOC. The SOC increase under NT cropping systems with diverse biomass-C inputs in RcCS did not lead to a significant difference from CT soil in the topsoil after five years. However, an increasing trend of SOC under NT soils over CT was observed. Nascente et al. (2013) revealed a similar increase in SOC at the 0-5 cm soil layer between NT and CT soils after two-year of NT rice cropping with cover crops in a tropical savanna climate. This report supports the occurrence of a starting point that stimulates the C restoration process. Zotarelli et al. (2007) emphasized that short-term changes in total SOC as a result of soil management practices are often difficult to detect. It was somewhat unexpected that NT, in combination with high crop residues returned to the soil, did not have a beneficial impact on SOC when compared with CT during this period, whereas SbCS and CsCS did have a beneficial impact on SOC. One explanation could be that biomass-C inputs retained in the NT soil surface over the experimental period were not adequate to significantly increase SOC when compared with those of CT soil. The annual biomass-C inputs from rice residues under CT-Rc (2.84 Mg ha^{-1}) were 30% and 76% higher than those of CT-Sb and CT-Cs, respectively. The biomass-C inputs from rice residues might contain higher lignin and lower N contents than soybean residues, leading to a lower SOC mineralization rate. The presence of legumes such as *Crotalaria sp.* can provide enough N to support the conversion of C from grasses to SOC (Boddey et al., 2010). In fine textured soils, clay- and silt-sized particles with high surface activities may chemically stabilize SOC and form the building blocks for aggregates that lead to the establishment of SOC physical protection (Six et al., 1999). With time, SOC under NT soils in RcCS might surpass that under CT soils because a higher trend was evident after five years in the present study.

CT practices involving the removal of crop residues can lead to a reduction in SOM due to accelerated decomposition and loss of topsoil that is rich in organic matter (Arshad, Schnitzer, Angers, & Ripmeester, 1990). Addition of crop residues to the soil is important because crop residues are a major source of C and N, which can replenish SOC and STN (Al-Kaisi et al., 2005). In the present study, CT soil still received the annual biomass-C inputs from crop residues which were maintained and spread in the soil surface resulting in a slight increase in SOC in the three cropping systems from 2011 to 2013. However, NT practices consistently outperformed the potential to sequester more SOC as a result of greater biomass-C inputs.

SOC stored at deeper depths may be in more stable forms (Angers & Eriksen-Hamel, 2008). SOC levels in the soil profile can be enhanced by the change in vegetation to deep-rooting crops that significantly affect the vertical distribution of SOC deep in the soil profile, acting as a potential C sink (Jobbágy & Jackson, 2000). The present study shows that NT with high biomass-C inputs potentially increases SOC in the top soil layer and most likely in the deep layers in the three cropping systems. This increase may be due to the rotation of main crops (i.e., rice, soybean, maize and cassava) with deep-rooted cover crops such as millet, sorghum, Congo grass and sunhemp that provide greater biomass-C inputs via roots. Séguy et al. (2006) reported that SOC in the subsoil could be sequestered by higher SOC rhizodeposition of deep rooting systems such as Congo grass, sorghum and *Crotalaria sp*. However, the subsoil consistently accumulated less SOC under than under CT in the three cropping systems. This finding was probably because the incorporation of forage species into crop rotations provides more root biomass inputs in the deep soil layers and seems to increase microbial activities (Lienhard et al., 2013). During the dry season, when no crops were planted in CT plots, SOC in NT soils could be degraded due to fresh C inputs in the subsoil from root exudates. Fresh C inputs cause an increase in SOC decomposition by microbes, which are also able to decompose the recalcitrant C compounds with their enzymes by using fresh C as a source of energy (Fontaine et al., 2007). Additionally, the incorporation of residues in the soil through disc plowing might result in greater deep soil SOC than under NT. This difference may be due to the slower decomposition of buried residues when compared with the residues left at the soil surface under NT, which may be susceptible to decomposition. Shan, Yang, Yan, and Wang (2005) reported that frequent tillage may accelerate the movement of SOM to deep soil layers. Thus, the results suggest that soils that have undergone NT for five years in this tropical agro-ecosystem have higher SOC in the surface layer than CT soils. However, SOC levels at lower depths are similar in both tillage systems or slightly higher under CT when sampling was extended to 100 cm depth. When compared with RV soil, SOC decreased in the order RV > NT > CT at only the 0-5 cm depth. This finding suggest that there is a greater potential for NT practices in the three cropping systems to restore SOC previously depleted by land conversion than there is for CT practices, due to the amount of biomass-C inputs via crop residues returned to the soil that could increase the SOC level. Tivet, Sá, Lal, Borszowskei, et al. (2013) found the restoration of SOC in tropical soils under NT crop rotations with cover crops leads to an increase in the resilience of agro-ecosystems.

Similar to SOC, STN in NT soil surface layer (especially that in the bi-annual rotation treatments in SbCS and CsCS) showed an increasing trend over that of CT. In contrast, the adoption of NT crop rotations with cover crops did increase STN in RcCS after five years. However, NT soils tended to accumulate more STN compared with CT soils at the surface layer, and a significant change might become evident with time. This finding is reflective of the differing amounts of above- and belowground crop biomass and types of crop residues returned to the soil. Grass and legume cover crops act as a source of supplemental N in the soil (Wagger, Cabrera, & Ranells, 1998), and so soil N can be increased by increasing in the amount of residue returned to the soil (Ghimire, Adhikari, Chen, Shah, & Dahal, 2012). In the present study, several grass and legume species such as Congo grass, millet, sorghum, stylo and sunhemp were rotated and/or associated with the main crops under NT systems. Thus, they could play a major role in providing N to the soil. Figueiredo, Resck, and Carneiro (2010) reported that adding crop residues added to the soil surface under NT systems led to an increase in STN. When comparing STN in 2011 and 2013, there were no noticeable changes in the three surface soil layers between CT and NT soils, with the exception of those under NT3 in the three cropping systems. However, a decrease in the four deeper layers was observed in most cases. This observation could be attributed to the fact that the inclusion of legume and grass species in the crop rotations increased root exudates and released more N in the subsoil. Consequently, N mineralization in the soils under NT systems surpassed CT soils due to higher microbial activities during the six-month dry season, as it happened to SOC.

3.4.2 Changes in particulate and mineral-associated organic C. Water soluble C (WSC) is the main energy and substrate source of soil microorganisms and is positively proportional to soil microbial biomass and activity. On average all depths in each cropping system (RcCS, SbCS, and CsCS), lost SOC during the physical fractionation process in the amounts of 7% in RV and NT soils to 13% in CT in 2011, representing greater WSC under RV and NT systems. Tivet, Sá, Lal, Borszowskei, et al. (2013) reported losses of SOC in bulk soil during fractionation ranged from 8% to approximately 15% on a clayed tropical Oxisol of the Brazilian Cerrado.

The decomposition process of crop residues, including the transition from particulate C fraction to mineral-associated C fraction, results in the stabilization of SOC with time (Bayer et al., 2001; Briedis, Sá, Caires, de Fátima Navarro, et al., 2012; Sá et al., 2001; Tivet, Sá, Lal, Borszowskei, et al., 2013). Particulate organic C (POC) is biologically and chemically active and is a part of the labile pool of SOM. POC is viewed as a good indicator of the quality of soil management systems (Cambardella & Elliott, 1992). Evaluation of the POC fraction might appear easy to assess, especially in the topsoil layer, which is primary location of potentially sequestered POC in short-term NT crop rotations with cover crops (Nascente et al., 2013). In general, NT practices in the three cropping systems resulted in a greater increase in POC in the surface layer after five years that that of CT practices. A possible explanation could be associated with greater biomass-C inputs via various cover crops placed on the surface of NT practices. The presence of significant differences in POC at 0-5 cm depth was observed in RcCS and CsCS. The bi-annual crop rotation treatments (NT2 and NT3) were likely to have greater increase in more POC than that of NT1. Although the adoption of NT crop rotations with cover crops did not result in a significant increase over CT in SbCS, NT practices tended to have higher POC in the topsoil that that of CT practices. This finding suggests that continuing NT cropping system practices with high biomass-C inputs from diversified crop species would result in a greater quantity of POC when compared with that of CT practices. Sá et al. (2001) indicated that there was an increase in the proportion of SOC concentrations in POC from crop residues added to the soil under NT (after conversion of CT to NT). The continuous biomass-C inputs from grass and legume cover crops act as a source of supplemental N to the soil (Wagger et al., 1998) that might result in a greater decrease of POC under NT than CT. Salvo, Hernández, and Ernst (2010) reported that N input may favor humification processes in POC. POC noticeably increased in all treatments in the three cropping systems from 2011 to 2013 but CT experienced the lowest increase. This increase was also observed in the deeper soil layers; fresh above- and belowground residue inputs from main deep rooting cover crops in the crop rotations could have contributed to this change. This finding contradicts other studies, which have shown that POC is strongly related to the quality and quantity of crop residues added to the soil and soil management practices (Alvarez, Alvarez, Daniel, Richter, & Blotta, 1998; Diekow et al., 2005; Vieira et al., 2007). Short-term NT cropping systems, in rotation or association with cover crops, have a greater potential to restore POC. Compared with soil POC under RV, NT crop rotations with diversified cover crops offered the potential to restore POC after five years in this study.

Mineral-associated organic C (MAOC) obtains stability from physical sorption to minerals and subsequently chemical bonds with the surface (Feller & Beare, 1997; Kaiser, Mikutta, & Guggenberger, 2007). It is highly stable to biological decomposition due to interaction with variably charged minerals (Bayer, Mielniczuk, Giasson, Martin-Neto, & Pavinato, 2006) so MAOC can be protected by its interaction with minerals. The changes in MAOC could be related to C migration from POC with time and bonding of SOC with soil colloids (Briedis, Sá, Caires, de Fátima Navarro, et al., 2012). In the present study, increased MAOC in the surface layer in the three cropping systems was consistently related to POC. Although the constant addition of biomass-C inputs under NT resulted in a MAOC increase, significant effects were detected only in SbCS. This increase could be related to the transition from POC to MAOC, which can stabilize SOC with time. The MAOC fraction comprised a major portion of SOC concentration (77%-96%) when compared with POC fraction. In most cases, MAOC concentrations increased with increasing depths. These results indicate that the soils used in this study have a good potential to contain large amounts of SOC due to high MAOC fractions that physically protect SOC. The presence of oxides and sesquioxides of iron and aluminum in Oxisols could act as binding agents between mineral particles and humic substances. Thus, significant effects of short-term CT systems on SOC depletion might be difficult to detect due to the high stability of clay and silt-sized microaggregates that result from physical SOC protection within the pores of microaggregates.

3.5 Conclusions

The main impact of short-term CA on SOC was found in the surface soil layer (0-5 cm) in SbCS and CsCS. Similarly, POC was affected only in the surface soil layer in RcCS and CsCS. Significant changes in SOC in RcCS and POC in SbCS under NT management practices might become evident with time, especially under bi-annual crop rotations. An increase in SOC and POC in soils under CT was still observed in this study and might have been related to the biomass-C inputs returned to soils after grain harvest of rice, soybean and maize, and root harvest of cassava (leaf inputs from cassava). The sequestration rates of intensive NT cropping systems with higher soil additions of biomass-C inputs led to enhanced SOC storage/ this constitutes an effective way to restore SOC over time. In this study, SOC and its size-fraction results suggest that bi-annual crop rotations are the appropriate crop rotation scheme to potentially restore SOC in the surface soil layer in a short-term CA and create a continuous flow in a clayed Cambodian Oxisol. These results also support the promising idea that SOC maybe vertically distributed in deeper layers in long-term CA in response to high biomass-C inputs from deep-rooting cover crops.

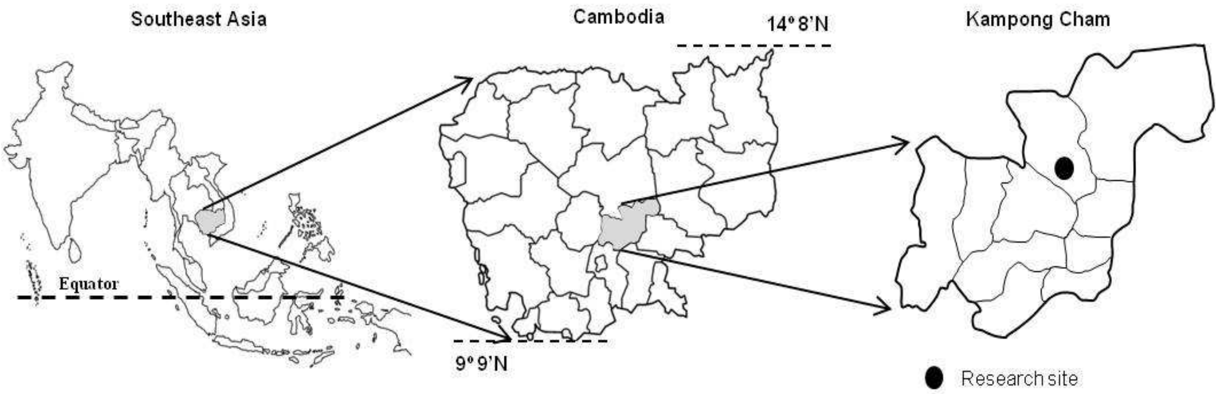
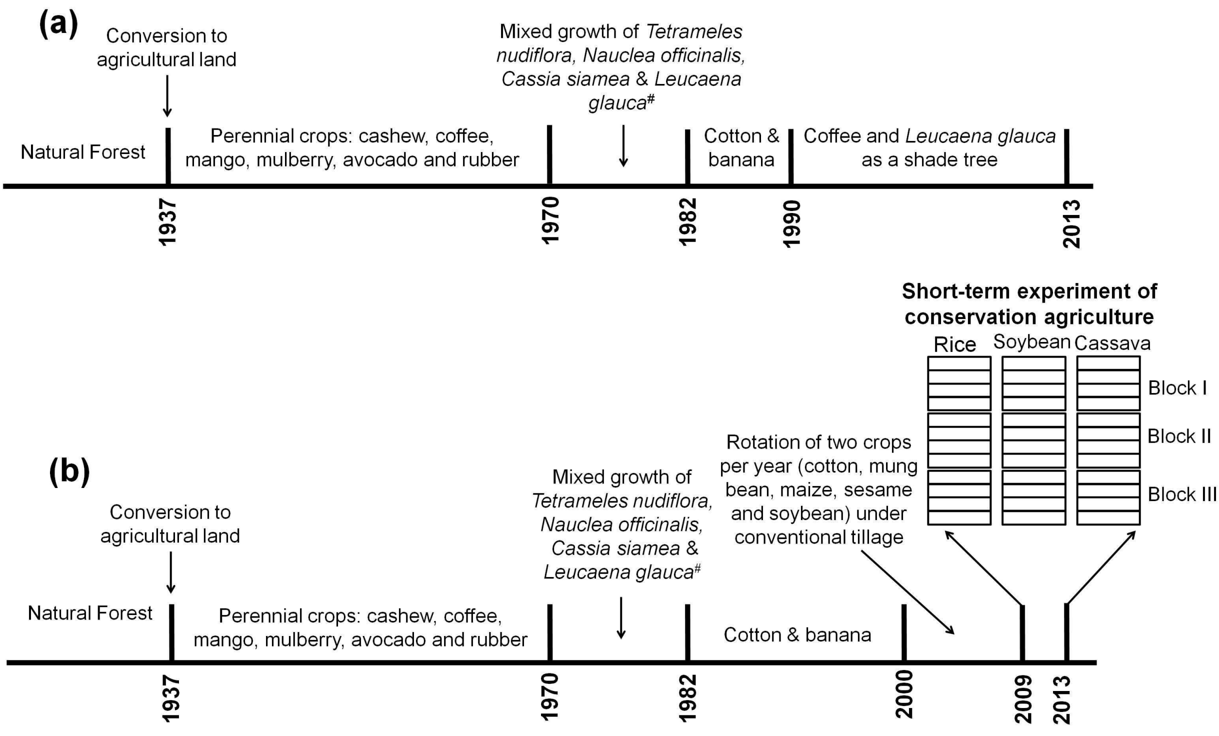


Figure 3.1. Location map of the research site.



Research Station was abandoned due to civil war (1970-1982).

Figure 3.2. Chronology of land use in the research site: (a) reference vegetation and (b) experimental site.

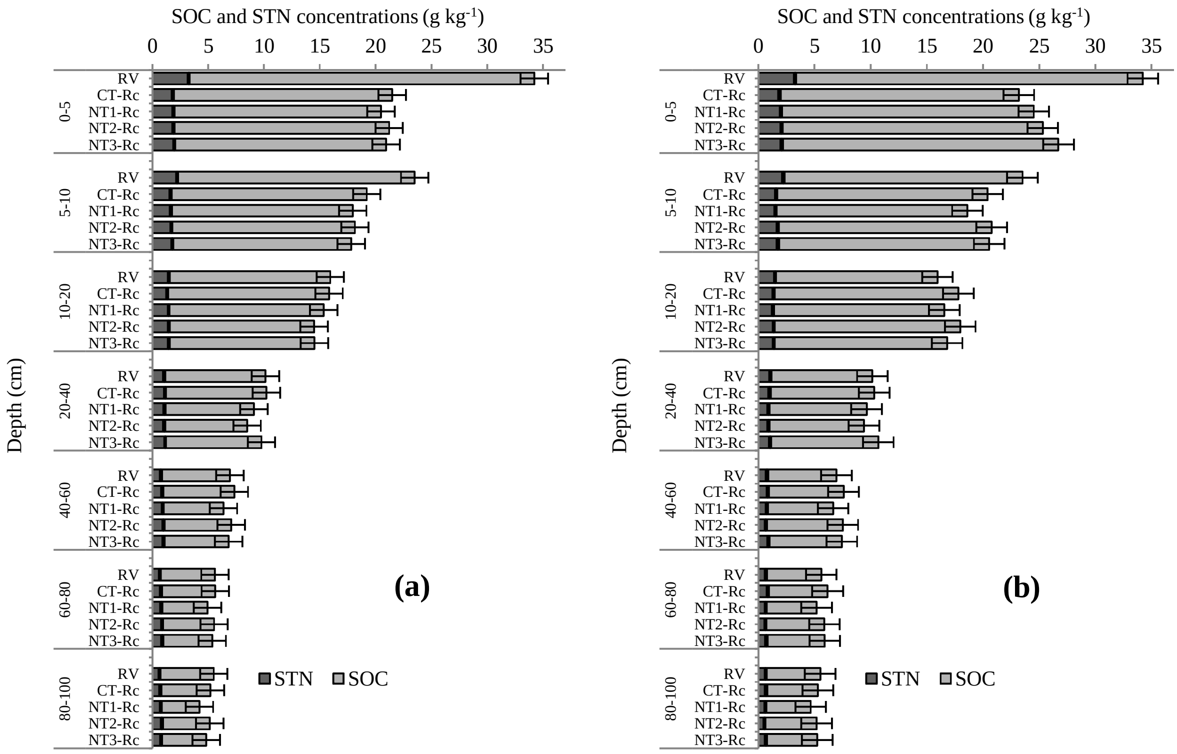


Figure 3.3. Soil total N (STN) and soil organic C (SOC) concentrations in soils at 0- to 100-cm depths under different soil management and crop sequences (RV: reference vegetation; CT-Rc: conventional tillage; NT-Rc: no-till) in rice-based cropping systems in (a) 2011 and (b) 2013. Error bars represent the standard error of the mean.

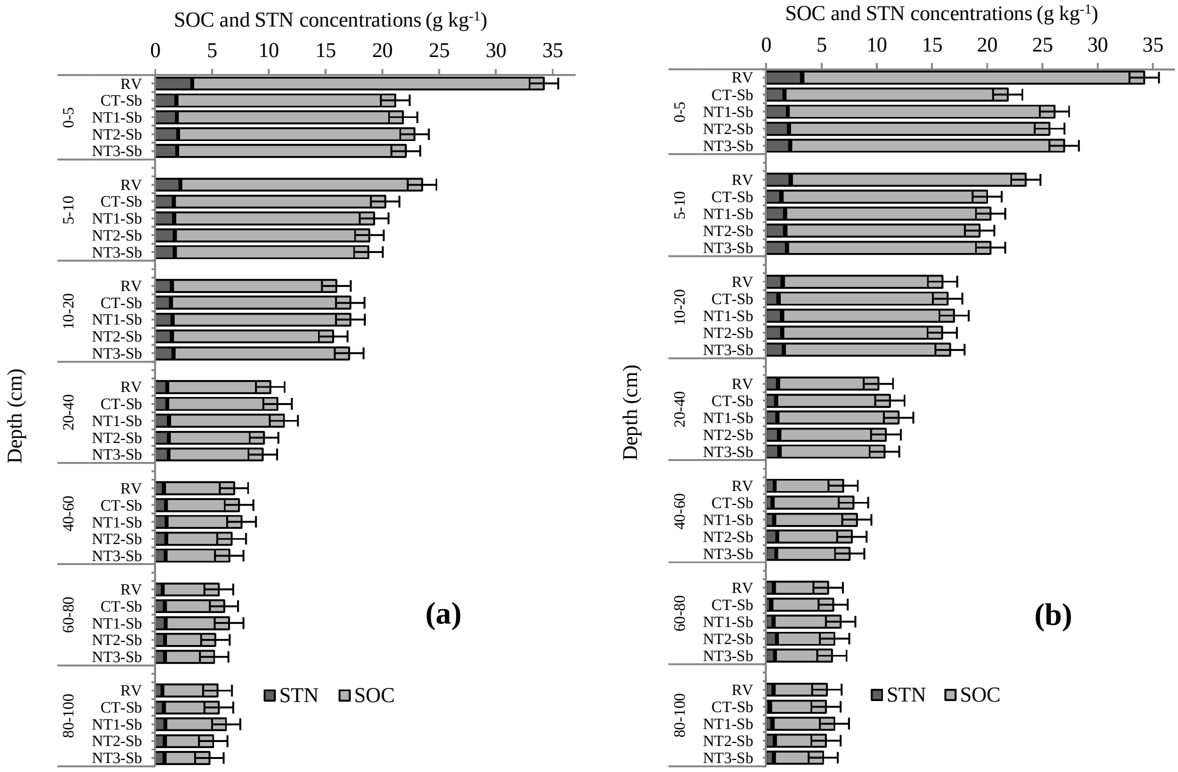
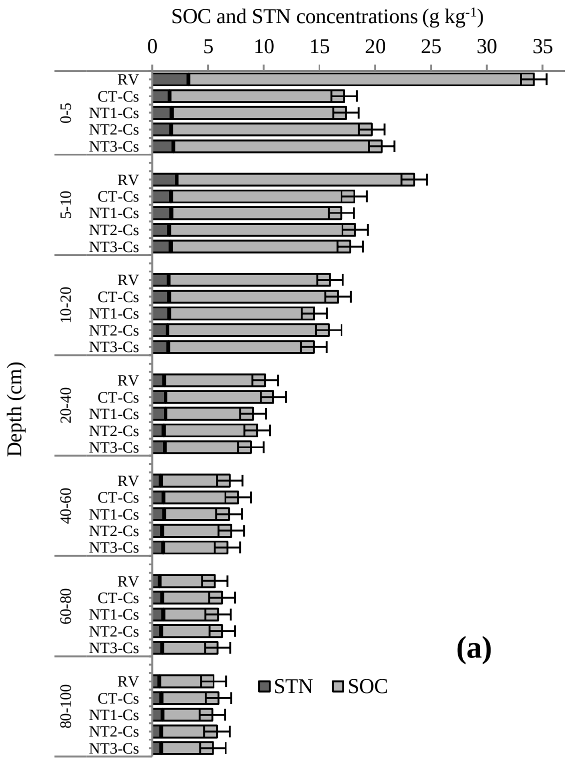


Figure 3.4. Soil total N (STN) and soil organic C (SOC) concentrations in soils at 0- to 100-cm depths under different soil management and crop sequences (RV: reference vegetation; CT-Rc: conventional tillage; NT-Rc: no-till) in soybean-based cropping systems in (a) 2011 and (b) 2013. Error bars represent the standard error of the mean.



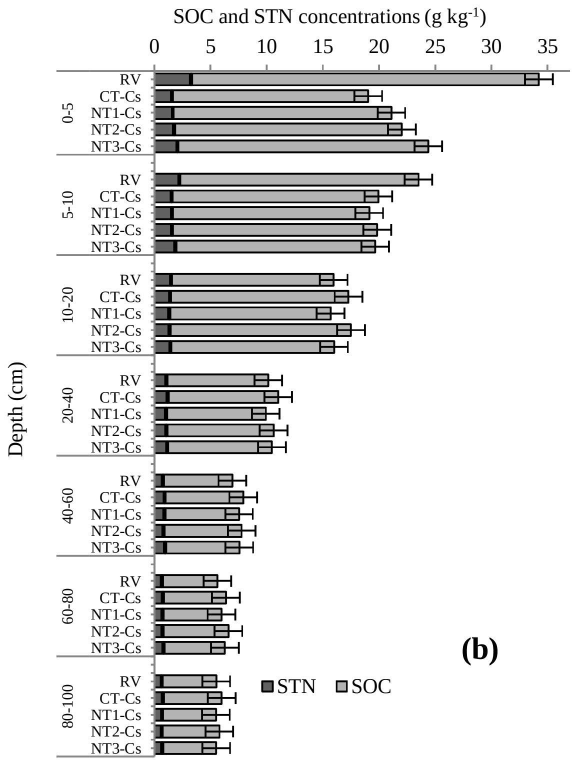


Figure 3.5. Soil total N (STN) and soil organic C (SOC) concentrations in soils at 0- to 100-cm depths under different soil management and crop sequences (RV: reference vegetation; CT-Rc: conventional tillage; NT-Rc: no-till) in cassava-based cropping systems in (a) 2011 and (b) 2013. Error bars represent the standard error of the mean.

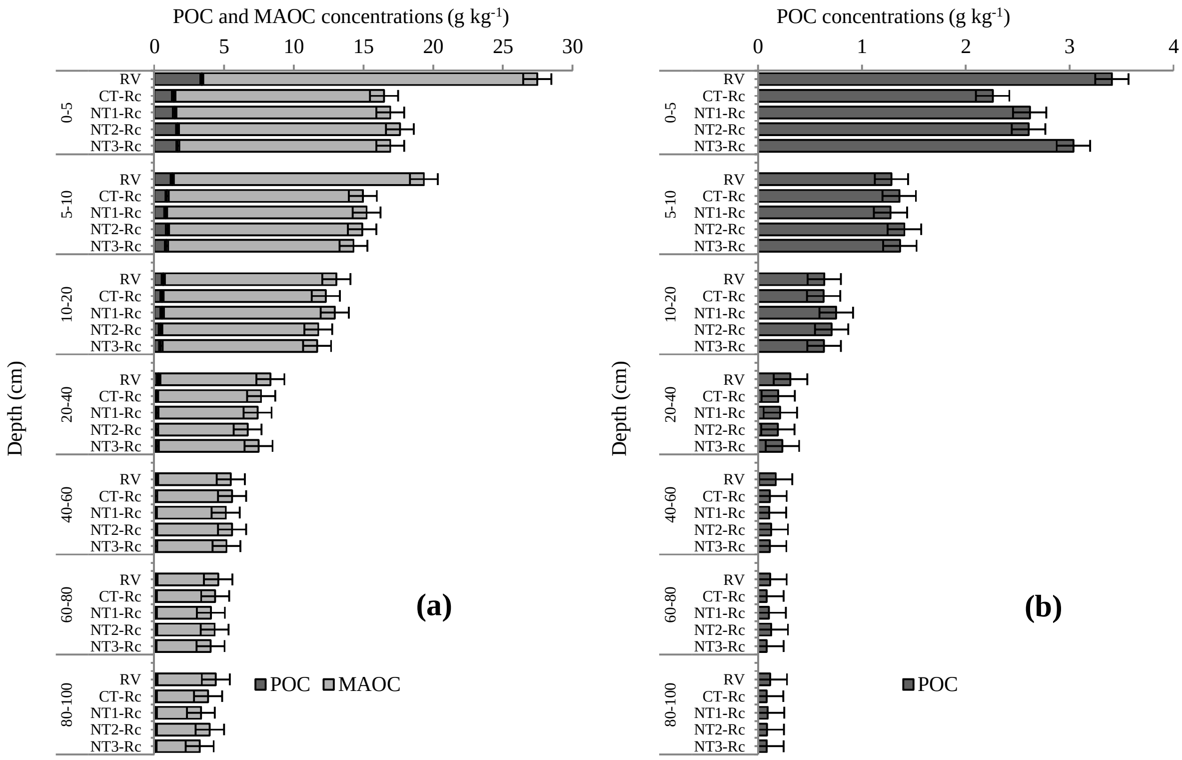


Figure 3.6. Particulate organic C (POC) and mineral-associated organic C (MAOC) concentrations in soils at 0- to 100-cm depths under different soil management and crop sequences (RV: reference vegetation; CT-Rc: conventional tillage; NT-Rc: no-till) in rice-based cropping systems in (a) 2011 and (b) 2013 (only POC presented). Error bars represent the standard error of the mean.

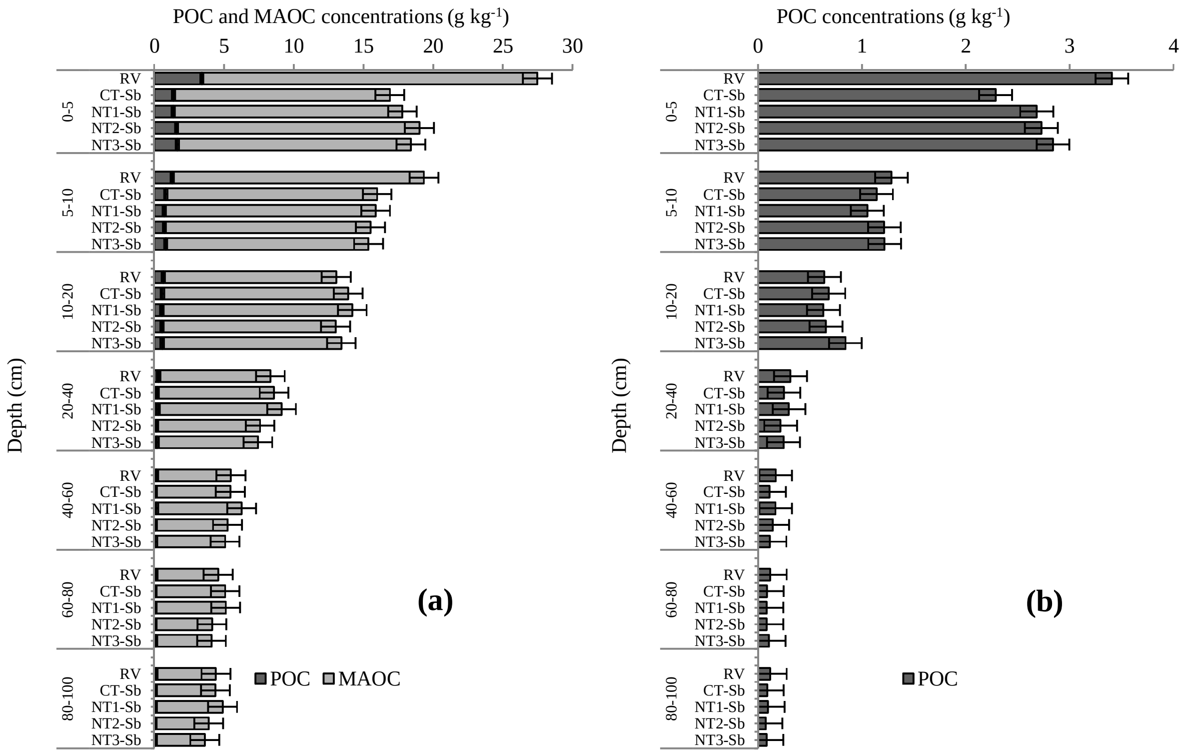


Figure 3.7. Particulate organic C (POC) and mineral-associated organic C (MAOC) concentrations in soils at 0- to 100-cm depths under different soil management and crop sequences (RV: reference vegetation; CT-Rc: conventional tillage; NT-Rc: no-till) in soybean-based cropping systems in (a) 2011 and (b) 2013 (only POC presented). Error bars represent the standard error of the mean.

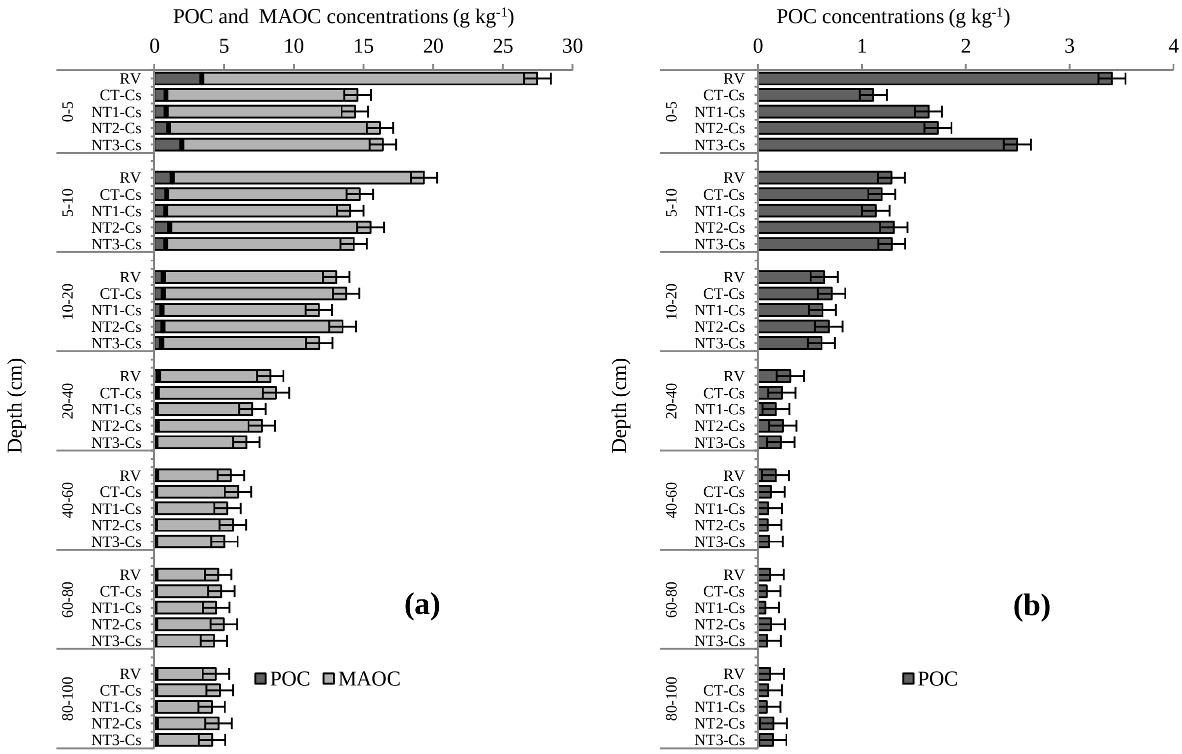


Figure 3.8. Particulate organic C (POC) and mineral-associated organic C (MAOC) concentrations in soils at 0- to 100-cm depths under different soil management and crop sequences (RV: reference vegetation; CT: conventional tillage; NT1-3: no-till) in cassava-based cropping systems in (a) 2011 and (b) 2013 (only POC presented). Error bars represent the standard error of the mean.

Table 3.1

Land use, crop sequence and C input in the five-year experiment period (2009-2013)

		C input (Mg ha^{-1})	
Land use	Crop sequence	Cumulative	Annual
Rice-based cropping systems			
CT-Rc	Mb/Rc – Mb/Rc – Mb/Rc – Mb/Rc – Mb/Rc	14.22	2.84
NT1-Rc	Mt/Rc+St – Mt+Cr/Rc+St – St(2010)/Rc+St – St(2011)[¥]/Rc+St – Mt+St(2012)/Rc+St	31.75	6.35
NT2-Rc	Mt/Rc+St – Mt+Cr+St (2009)/Mz+St – Mt+Cr+St (2010)/Rc+St – St(2011)/Mz+St – St (2012)/Rc+St	30.29	6.06
NT3-Rc	Mt/Mz+St – Mt+Cr+St (2009)/Rc+St – St (2010)/Mz+St – St (2011)/Rc+St – St (2012)/Mz+St	33.64	6.73
Soybean-based cropping systems			
CT-Sb	Se/Sb – Se/Sb – Se/Sb – Se/Sb – Se/Sb	10.96	2.19
NT1-Sb	Mt/Sb+Brz – Brz(2009)/Sb+St – Mt/Sb+St+Sg – Mt/Sb+St – Sr+St (2012)/Sb+St+Sg	36.62	7.32
NT2-Sb	Mt+/Sb+St – Mt+Cr+St (2009)/Mz+St – Mt/Sb+St – Mt+Cr/Mz+St – Sr+St (2012)/Sb+St	35.47	7.09
NT3-Sb	Mt/Mz+Brz – Mt/Sb+St – Mt+Cr/Mz+St – St (2011)/Sb+St – Sg+Cr+St (2012)/Mz+St	39.25	7.85
Cassava-based cropping systems			
CT-Cs	Cs – Cs – Cs – Cs – Cs	8.06	1.61
NT1-Cs	Cs+St – Cs+St – Cs+St – Cs+St – Cs+St	19.54	3.91
NT2-Cs	Cs+St – Mt+St (2009)/Mz+St – St (2010)/Cs+St – Mt+Cr+St (2011)/Mz+St – St (2012)/Cs+St	21.70	4.34
NT3-Cs	Mt/Mz+St – Cs+St – Mt+Cr+St (2010)/Mz+St – Cs+St – Mt+Cr+St (2012)/Mz3ed c+St	25.27	5.05

Mb: mung bean (*Vigna radiata*); Rc: rice (*Oryza sativa* L.); Mt: millet (*Pennisetum typhoides* Burm); St: *Stylosanthes guianensis*; Cr: *Crotalaria juncea*; Mz: maize (*Zea mays* L.); Se: sesame (*Sesamum indicum*); Sb: soybean (*Glycine max* (L.) Merr.); Brz: *Brachiaria ruziziensis* cv. ruzi; Cs: cassava (*Manihot esculenta*); Sg: sorghum (*Sorghum bicolor* L.) [¥] St (*Stylosanthes guianensis)* left from the year in brackets. "/" indicates relay cropping with varying planting dates; "+" indicates crops planted in association (same or staggered sowing dates).

Table 3.2

Mineral fertilizer rates applied to crops during the experiment period (2009–2013)

Annual mineral fertilizer rate	Crops	Year					Total fertilizer inputs
		2009	2010	2011	2012	2013	
P_2O_5 (kg ha^{-1})	All crops	80	32	32	32	32	208
N (kg ha^{-1})	Rice	69	46	46	46	46	253
	Soybean†	23	23	23	23	23	115
	Cassava	92	69	69	69	69	368
	Maize	92	69	69	69	69	368
K_2O (kg ha^{-1})	Rice	60	30	30	30	30	180
	Soybean	60	60	60	60	60	300
	Cassava	60	90	60	60	60	330
	Maize	60	30	30	30	30	180

† 23 kg N ha^{-1} were applied at sowing to soybean under NT based systems, not under CT

Table 3.3

Soil attributes in 0- to 100-cm depths under reference vegetation and experimental plots in 2011

Land use	Depth (cm)	Soil attributes										
		Sand	Silt	Clay	pH	H+Al	Al^{3+}	Ca^{2+}	Mg^{2+}	K^{+}	CEC	P
		g kg^{-1}			($CaCl_2$)	*cmol dm^{-3}*						*mg dm^{-3}*
RV	0–5	0.82	425	567	5.1	6.71	0.03	9.62	3.52	1.14	21.03	98.4
	5–10	1.91	368	613	5.1	6.22	0.00	7.63	2.53	0.77	17.04	68.9
	10–20	1.30	334	653	5.0	6.06	0.03	5.35	2.12	0.56	14.05	60.7
	20–40	1.10	282	707	4.9	6.12	0.13	3.58	1.58	0.36	11.73	78.2
	40–60	0.69	246	747	4.5	6.85	0.32	2.38	1.08	0.35	10.74	79.5
	60–80	0.55	224	770	4.4	7.52	0.60	1.93	1.08	0.35	10.92	86.0
	80–100	0.61	214	780	4.5	7.45	0.52	1.77	1.15	0.33	10.84	77.8
CT†	0–5	1.27	300	688	4.8	7.20	0.18	4.78	1.88	0.74	14.62	55.1
	5–10	1.38	293	693	4.8	7.29	0.18	4.69	1.66	0.62	14.41	51.5
	10–20	1.25	284	703	4.7	7.51	0.23	4.18	1.33	0.43	13.48	46.0
	20–40	0.93	257	733	4.8	6.33	0.19	3.45	1.02	0.23	11.10	45.6
	40–60	0.78	240	752	4.8	5.96	0.21	2.78	0.81	0.12	9.67	39.2
	60–80	0.69	225	768	4.8	5.85	0.34	2.56	0.74	0.11	9.28	28.2
	80–100	0.75	210	782	4.7	5.74	0.27	2.37	0.77	0.12	8.98	29.3
NT‡	0–5	1.52	306	680	4.8	7.19	0.17	4.67	2.23	0.81	14.97	52.08
	5–10	1.37	293	695	4.6	7.97	0.35	3.81	1.59	0.57	14.02	46.19
	10–20	1.24	279	710	4.7	7.60	0.31	3.65	1.24	0.36	12.93	46.31
	20–40	0.83	252	740	4.7	6.54	0.24	2.84	0.91	0.19	10.54	45.43
	40–60	0.79	236	757	4.6	6.29	0.29	2.19	0.71	0.12	9.35	34.74
	60–80	0.75	227	767	4.5	6.40	0.37	1.84	0.67	0.12	9.10	30.24
	80–100	0.65	219	775	4.4	6.81	0.49	1.54	0.80	0.13	9.32	32.65

RV: reference vegetation; CT: conventional plow-based tillage; NT: no-tillage; † and ‡ Mean values of the three CT and nine NT systems, respectively, of three production systems were used for the quantification of soil attributes. CEC (cation exchange capacity) was determined by summation of potential acidity and exchangeable bases (Ca + Mg + K).

Table 3.4

Soil bulk density (ρb) (Mg m-3) in 0- to 100-cm soil depths under adjacent reference vegetation (RV), and rice- (RcCS), soybean- (SbCS) and cassava- (CsCS) based cropping systems in 2011

Land use	Soil depth (cm)						
	0–5	5–10	10–20	20–40	40–60	60–80	80–100
RcCS							
RV[a]	1.00 B	1.05 B	1.10 B	1.14 ns	1.12 A	1.05 ns	1.06 ns
CT-Rc[b]	1.17 A ns	1.21 A ns	1.20 A ns	1.07	1.00 C ns	1.11	1.10
NT1-Rc	1.20 A	1.20 A	1.20 A	1.10	1.05 ABC	1.05	1.08
NT2-Rc	1.20 A	1.23 A	1.18 A	1.13	1.03 C	1.09	1.16
NT3-Rc	1.21 A	1.22 A	1.22 A	1.08	1.09 AB	1.13	1.15
SbCS							
RV[a]	1.00 B	1.05 B	1.10 ns	1.14 ns	1.12 ns	1.05 ns	1.06 ns
CT-Sb[b]	1.16 A ns	1.22 A ns	1.25	1.11	1.06	1.07	1.10 ab
NT1-Sb	1.16 A	1.25 A	1.23	1.20	1.07	1.08	1.07 b
NT2-Sb	1.16 A	1.19 A	1.16	1.11	1.08	1.09	1.14 a
NT3-Sb	1.14 A	1.18 A	1.22	1.06	1.04	1.05	1.13 a
CsCS							
RV[a]	1.00 B	1.05 C	1.10 ns	1.14 ns	1.12 ns	1.05 ns	1.06 ns
CT-Cs[b]	1.10 A ns	1.11 BCns	1.15	1.12	1.02	0.99	1.06
NT1-Cs	1.17 A	1.19 A	1.25	1.18	1.02	1.09	1.11
NT2-Cs	1.17 A	1.18 AB	1.25	1.17	1.04	1.11	1.08
NT3-Cs	1.17 A	1.18 AB	1.24	1.13	1.03	1.04	1.09

RV: reference vegetation; CT: conventional plow-based tillage; NT: no-tillage; [a] Comparison between tillage systems CT, NT1, NT2, NT3 and reference vegetation (RV). Uppercase letters within the same column indicate difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison between tillage systems CT, NT1, NT2 and NT3. Lowercase letters within the same column indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 3.5

SOC stocks (Mg ha^{-1}), on an equivalent soil-depth, in 0- to 100-cm soil depths under rice-based cropping systems

Soil depth (cm)	PE	RV[a*]	CT-Rc[b]	NT1-Rc	NT2-Rc	NT3-Rc
2009						
0–5	8.8					
5–10	8.8					
10–20	16.5					
20–40	22.2					
2011						
0–5		15.5 A	9.8 B ns	9.3 B	9.7 B	9.5 B
5–10		11.2 A	9.2 B ns	8.5 B	8.6 B	8.4 B
10–20		16.0 ns	16.0	15.3	14.4	14.4
20–40		20.7 ns	20.8	18.3	17.0	19.7
40–60		13.8 ns	14.5	12.2	13.6	13.0
60–80		10.3 ns	10.2	8.7	9.8	9.4
80–100		10.2 A	9.6 A ns	7.3 B	9.2 A	8.5 AB
0-100		97.7 A	90.1 ABns	79.6 B	82.3 B	82.9 B
2013						
0–5		15.5 A	10.6 B ns	11.2 B	11.6 B	12.3 B
5–10		11.2 ns	9.9	9.0	10.0	9.9
10–20		16.0 ns	18.1	16.9	18.3	17.1
20–40		20.7 ns	21.3	19.9	19.4	22.0
40–60		13.8 ns	15.1	13.2	15.3	14.6
60–80		10.3 ns	11.2	9.5	11.0	10.9
80–100		10.2 ns	9.8	8.6	9.9	9.7
0-100		97.7 ns	96.0	87.4	95.5	96.5

PE: prior to experiment establishment; RV: reference vegetation; CT: conventional tillage; NT: no-till; [a] Comparison between tillage systems CT-Rc, NT1-Rc, NT2-Rc, NT3-Rc and RV; Uppercase letters within the same line in each cropping system indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [*] RV collected in 2011 is used for both 2011 and 2013. [b] Comparison among tillage systems CT-Rc, NT1-Rc, NT2-Rc and NT3-Rc; Lowercase letters within the same line indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 3.6

Soil total N stocks (Mg ha^{-1}), on an equivalent soil-depth, in 0- to 100-cm soil depths under rice-based cropping systems

Soil depth (cm)	PE	RV[a*]	CT-Rc[b]	NT1-Rc	NT2-Rc	NT3-Rc
2009						
0–5	0.90					
5–10	0.85					
10–20	1.67					
20–40	2.60					
2011						
0–5		1.63 A	0.91 B ns	0.94 B	0.94 B	0.98 B
5–10		1.16 A	0.86 B ns	0.87 B	0.90 B	0.94 B
10–20		1.63 ns	1.48	1.61	1.62	1.61
20–40		2.42 ns	2.59	2.47	2.42	2.63
40–60		1.72 C	1.96 BC ns	2.06 AB	2.21 A	2.22 A
60–80		1.41 B	1.62 ABns	1.68 AB	1.82 A	1.85 A
80–100		1.36 ns	1.51	1.60	1.80	1.67
0-100		11.33 ns	10.93	11.23	11.71	11.90
2013						
0–5		1.63 A	0.94 B ns	1.00 B	1.03 B	1.04 B
5–10		1.16 A	0.83 BC ns	0.80 C	0.91 B	0.91 B
10–20		1.63 ns	1.50	1.42	1.50	1.52
20–40		2.42 ns	2.27	2.06	2.05	2.37
40–60		1.72 ns	1.88	1.68	1.51	1.99
60–80		1.41 ns	1.77	1.33	1.30	1.52
80–100		1.36 ns	1.47	1.31	1.17	1.46
0-100		11.33A	10.66 ABns	9.60BC	9.47 C	10.81 A

PE: prior to experiment establishment; RV: reference vegetation; CT: conventional tillage; NT: no-till; [a] Comparison between tillage systems CT-Rc, NT1-Rc, NT2-Rc, NT3-Rc and RV; Uppercase letters within the same line in each cropping system indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [*] RV collected in 2011 is used for both 2011 and 2013. [b] Comparison among tillage systems CT-Rc, NT1-Rc, NT2-Rc and NT3-Rc; Lowercase letters within the same line indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 3.7

SOC stocks (Mg ha^{-1}), on an equivalent soil-depth, in 0- to 100-cm soil depths under soybean-based cropping systems

Soil depth (cm)	PE	RV[a*]	CT-Sb[b]	NT1-Sb	NT2-Sb	NT3-Sb
2009						
0–5	9.4					
5–10	9.3					
10–20	16.8					
20–40	20.7					
2011						
0–5		15.5 A	9.6 Bc	9.9 Bbc	10.4 Ba	10.0 Bab
5–10		11.2 A	9.8 B ns	9.2 B	9.0 B	9.0 B
10–20		16.0 ns	17.4	17.3	15.7	17.0
20–40		20.7 ns	22.1	23.1	19.1	19.0
40–60		13.8 ns	14.4	14.7	12.8	12.5
60–80		10.3 ns	11.0	11.7	9.3	9.1
80–100		10.2 ns	10.2	11.5	9.1	8.4
0-100		97.7 ns	94.5	97.4	85.4	85.0
2013						
0–5		15.5 A	10.1 Cb	12.1 Ba	11.8 Ba	12.4 Ba
5–10		11.2 A	9.8 B ns	9.8 B	9.2 B	9.7 B
10–20		16.0 ns	16.9	17.2	16.0	16.6
20–40		20.7 ns	23.5	25.1	22.0	21.7
40–60		13.8 ns	16.4	16.7	15.1	14.9
60–80		10.3 ns	11.8	12.8	11.0	10.8
80–100		10.2 ns	10.7	12.0	9.9	9.5
0-100		97.7 ns	99.2	105.7	95.0	95.6

PE: prior to experiment establishment; RV: reference vegetation; CT: conventional tillage; NT: no-till; [a] Comparison between tillage systems CT-Sb, NT1-Sb, NT2-Sb, NT3-Sb and RV; Uppercase letters within the same line in each cropping system indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [*] RV collected in 2011 is used for both 2011 and 2013. [b] Comparison among tillage systems CT-Sb, NT1-Sb, NT2-Sb and NT3-Sb; Lowercase letters within the same line indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 3.8

Soil total N stocks (Mg ha^{-1}), on an equivalent soil-depth, in 0- to 100-cm soil depths under soybean-based cropping systems

Soil depth (cm)	PE	RV[a*]	CT-Sb[b]	NT1-Sb	NT2-Sb	NT3-Sb
2009						
0–5	0.89					
5–10	0.90					
10–20	1.68					
20–40	2.33					
2011						
0–5		1.63 A	0.93 B ns	0.96 B	1.01 B	0.97 B
5–10		1.16 A	0.87 B ns	0.88 B	0.90 B	0.90 B
10–20		1.63 ns	1.54	1.69	1.62	1.78
20–40		2.42 ns	2.44	2.79	2.74	2.71
40–60		1.72 B	2.12 A ns	2.26 A	2.20 A	2.10 A
60–80		1.41 C	1.78 B ns	1.97 A	1.85 AB	1.80 AB
80–100		1.36 C	1.63 B ns	1.90 A	1.81 AB	1.74 AB
0-100		11.33 ns	11.31	12.45	12.13	12.00
2013						
0–5		1.63 A	0.82 Cb	0.98 Ba	1.02 Ba	1.08 Ba
5–10		1.16 A	0.72 Cb	0.89 Ba	0.90 Ba	0.99 Ba
10–20		1.63 ns	1.23	1.57	1.59	1.74
20–40		2.42 AB	2.04 Bc	2.29 Bbc	2.70 Aab	2.74 Aa
40–60		1.72 ns	1.25	1.62	2.22	2.01
60–80		1.41 BC	0.92 Cb	1.37 BCab	2.01 Aa	1.66 ABa
80–100		1.36 ns	0.69	1.20	1.71	1.47
0-100		11.33 A	7.67 Bb	9.92 ABab	12.15 Aa	11.69 Aa

PE: prior to experiment establishment; RV: reference vegetation; CT: conventional tillage; NT: no-till; [a] Comparison between tillage systems CT-Sb, NT1-Sb, NT2-Sb, NT3-Sb and RV; Uppercase letters within the same line in each cropping system indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [*] RV collected in 2011 is used for both 2011 and 2013. [b] Comparison among tillage systems CT-Sb, NT1-Sb, NT2-Sb and NT3-Sb; Lowercase letters within the same line indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 3.9

SOC stocks (Mg ha^{-1}), on an equivalent soil-depth, in 0- to 100-cm soil depths under cassava-based cropping systems

Soil depth (cm)	PE	RV[a*]	CT-Cs[b]	NT1-Cs	NT2-Cs	NT3-Cs
2009						
0–5	8.2					
5–10	8.2					
10–20	16.8					
20–40	23.3					
2011						
0–5		15.5 A	7.8 Cb	7.8 Cb	9.0 BCa	9.3 Ba
5–10		11.2 A	8.6 B ns	8.0 B	8.8 B	8.4 B
10–20		16.0 ns	16.7	14.3	15.9	14.4
20–40		20.7 ns	22.1	17.9	19.1	17.7
40–60		13.8 ns	14.9	13.0	13.9	13.0
60–80		10.3 ns	11.2	10.3	11.5	10.4
80–100		10.2 ns	10.9	9.4	10.7	9.7
0-100		97.7 ns	92.2	80.7	88.9	82.9
2013						
0–5		15.5 A	8.7 Dc	9.7 CDbc	10.1 BCab	11.1 Ba
5–10		11.2 ns	9.7	9.2	9.6	9.3
10–20		16.0 ns	17.5	15.9	17.8	16.0
20–40		20.7 ns	22.5	20.2	21.8	21.3
40–60		13.8 ns	15.7	14.9	15.6	14.8
60–80		10.3 ns	11.7	11.0	12.3	11.4
80–100		10.2 ns	11.1	10.1	10.9	10.1
0-100		97.7 ns	96.9	91.0	98.1	94.1

PE: prior to experiment establishment; RV: reference vegetation; CT: conventional tillage; NT: no-till; [a] Comparison between tillage systems CT-Sb, NT1-Cs, NT2-Cs, NT3-Cs and RV; Uppercase letters within the same line in each cropping system indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [*] RV collected in 2011 is used for both 2011 and 2013. [b] Comparison among tillage systems CT-Cs, NT1-Cs, NT2-Cs and NT3-Cs; Lowercase letters within the same line indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 3.10

Soil total N stocks (Mg ha^{-1}), on an equivalent soil-depth, in 0- to 100-cm soil depths under cassava-based cropping systems

Soil depth (cm)	PE	RV[a*]	CT-Cs[b]	NT1-Cs	NT2-Cs	NT3-Cs
2009						
0–5	0.85					
5–10	0.80					
10–20	1.68					
20–40	2.87					
2011						
0–5		1.63 A	0.78 C ns	0.87 BC	0.85 BC	0.95 B
5–10		1.16 A	0.89 B ns	0.90 B	0.80 B	0.87 B
10–20		1.63 ns	1.68	1.70	1.52	1.59
20–40		2.42 ns	2.76	2.73	2.33	2.56
40–60		1.72 C	2.26 ABns	2.39 A	1.98 BC	2.17 AB
60–80		1.41 C	1.90 ABns	2.09 A	1.67 BC	1.89 AB
80–100		1.36 ns	1.76	1.95	1.71	1.72
0-100		11.33 ns	12.03	12.63	10.86	11.75
2013						
0–5		1.63 A	0.78 Cc	0.81 Cbc	0.88 Cb	1.02 Ba
5–10		1.16 A	0.80 Cb	0.82 Cb	0.82 Cb	0.98 Ba
10–20		1.63 ns	1.53	1.45	1.47	1.56
20–40		2.42 ns	2.69	2.38	2.40	2.59
40–60		1.72 C	2.04 ABns	1.99 ABC	1.80 BC	2.13 A
60–80		1.41 ns	1.61	1.54	1.52	1.73
80–100		1.36 ns	1.61	1.47	1.38	1.48
0-100		11.33 ns	11.06	10.46	10.27	11.49

PE: prior to experiment establishment; RV: reference vegetation; CT: conventional tillage; NT: no-till; [a] Comparison between tillage systems CT-Sb, NT1-Cs, NT2-Cs, NT3-Cs and RV; Uppercase letters within the same line in each cropping system indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [*] RV collected in 2011 is used for both 2011 and 2013. [b] Comparison among tillage systems CT-Cs, NT1-Cs, NT2-Cs and NT3-Cs; Lowercase letters within the same line indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 3.11

POC stocks (Mg ha^{-1}), on an equivalent soil-depth, in 0- to 100-cm soil depths under rice-based cropping systems

Soil depth (cm)	RV[a*]	CT-Rc[b]	NT1-Rc	NT2-Rc	NT3-Rc
2011					
0–5	1.70 A	0.70 B ns	0.73 B	0.83 B	0.84 B
5–10	0.67 ns	0.48	0.43	0.50	0.45
10–20	0.70 ns	0.61	0.61	0.50	0.52
20–40	0.71 A	0.39 B ns	0.41 B	0.35 B	0.45 B
40–60	0.38 A	0.20 B ns	0.18 B	0.23 B	0.19 B
60–80	0.24 ns	0.14	0.17	0.20	0.12
80–100	0.24 ns	0.15	0.14	0.15	0.12
0-100	4.64 A	2.67 B ns	2.67 B	2.76 B	2.69 B
2013					
0–5	1.70 A	1.13 Cb	1.31 BCab	1.30 BCab	1.52 ABa
5–10	0.67 ns	0.71	0.67	0.74	0.72
10–20	0.70 ns	0.69	0.83	0.78	0.70
20–40	0.71 ns	0.44	0.49	0.43	0.53
40–60	0.38 ns	0.25	0.24	0.28	0.25
60–80	0.24 ns	0.17	0.22	0.27	0.18
80–100	0.24 ns	0.18	0.19	0.18	0.18
0-100	4.64 ns	3.57	3.95	3.98	4.08

PE: prior to experiment establishment; RV: reference vegetation; CT: conventional tillage; NT: no-till; [a] Comparison between tillage systems CT-Rc, NT1-Rc, NT2-Rc, NT3-Rc and RV; Uppercase letters within the same line in each cropping system indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [*] RV collected in 2011 is used for both 2011 and 2013. [b] Comparison among tillage systems CT-Rc, NT1-Rc, NT2-Rc and NT3-Rc; Lowercase letters within the same line indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 3.12

MAOC stocks (Mg ha^{-1}), on an equivalent soil-depth, in 0- to 100-cm soil depths under rice-based cropping systems in 2011

Soil depth (cm)	RV[a*]	CT-Rc[b]	NT1-Rc	NT2-Rc	NT3-Rc
0–5	12.01 A	7.54 B ns	7.72 B	7.96 B	7.61 B
5–10	9.47 A	7.37 B ns	7.56 B	7.32 B	7.06 B
10–20	13.69 ns	12.96	13.65	12.47	12.40
20–40	18.29 ns	17.11	16.52	14.95	16.64
40–60	11.91 ns	12.25	11.28	12.20	11.37
60–80	9.34 ns	9.03	8.32	8.89	8.34
80–100	9.07 A	8.06 Aa	6.96 Bb	8.33 Aa	6.84 Bb
0-100	83.78 A	74.32 B ns	72.01 B	72.12 B	70.26 B

PE: prior to experiment establishment; RV: reference vegetation; CT: conventional tillage; NT: no-till; [a] Comparison between tillage systems CT-Rc, NT1-Rc, NT2-Rc, NT3-Rc and RV; Uppercase letters within the same line in each cropping system indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [*] RV collected in 2011 is used for both 2011 and 2013. [b] Comparison among tillage systems CT-Rc, NT1-Rc, NT2-Rc and NT3-Rc; Lowercase letters within the same line indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 3.13

POC stocks (Mg ha^{-1}), on an equivalent soil-depth, in 0- to 100-cm soil depths under soybean-based cropping systems

Soil depth (cm)	RV[a*]	CT-Sb[b]	NT1-Sb	NT2-Sb	NT3-S
2011					
0–5	1.70 A	0.69 B ns	0.67 B	0.80 B	0.82 B
5–10	0.67 A	0.43 B ns	0.37 B	0.38 B	0.43 B
10–20	0.70 ns	0.64	0.60	0.60	0.62
20–40	0.71 ns	0.49	0.62	0.38	0.46
40–60	0.38 A	0.17 Bb	0.35 Aa	0.15 Bb	0.20 Bb
60–80	0.24 ns	0.13	0.13	0.10	0.21
80–100	0.24 A	0.14 B ns	0.14 B	0.12 B	0.14 B
0-100	4.64 A	2.69 BCns	2.86 B	2.53 C	2.88 B
2013					
0–5	1.70 ns	1.14	1.34	1.36	1.42
5–10	0.67 ns	0.60	0.55	0.64	0.64
10–20	0.70 ns	0.75	0.70	0.72	0.92
20–40	0.71 ns	0.57	0.67	0.49	0.56
40–60	0.38 ns	0.24	0.37	0.31	0.25
60–80	0.24 ns	0.18	0.17	0.18	0.22
80–100	0.24 ns	0.19	0.20	0.16	0.18
0-100	4.64 A	3.67 Bns	4.00 B	3.86 B	4.19 AB

PE: prior to experiment establishment; RV: reference vegetation; CT: conventional tillage; NT: no-till; [a] Comparison between tillage systems CT-Sb, NT1-Sb, NT2-Sb, NT3-Sb and RV; Uppercase letters within the same line in each cropping system indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [*] RV collected in 2011 is used for both 2011 and 2013. [b] Comparison among tillage systems CT-Sb, NT1-Sb, NT2-Sb and NT3-Sb; Lowercase letters within the same line indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 3.14

MAOC stocks (Mg ha^{-1}), on an equivalent soil-depth, in 0- to 100-cm soil depths under soybean-based cropping systems in 2011

Soil depth (cm)	RV[a*]	CT-Sb[b]	NT1-Sb	NT2-Sb	NT3-S
0–5	12.01 A	7.75 Cc	8.21 BCb	8.70 Ba	8.36 BCab
5–10	9.47 A	7.96 B ns	7.96 B	7.76 B	7.63 B
10–20	13.69 ns	14.71	15.09	13.76	14.17
20–40	18.29 ns	19.09	20.27	16.91	16.52
40–60	11.91 B	12.04 Bb	13.66 Aa	11.59 Bb	11.15 Bb
60–80	9.34 ns	10.62	10.65	8.63	8.00
80–100	9.07 ns	9.08	10.36	8.22	7.57
0-100	83.78 ns	81.25	86.20	75.57	73.40

PE: prior to experiment establishment; RV: reference vegetation; CT: conventional tillage; NT: no-till; [a] Comparison between tillage systems CT-Sb, NT1-Sb, NT2-Sb, NT3-Sb and RV; Uppercase letters within the same line in each cropping system indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [*] RV collected in 2011 is used for both 2011 and 2013. [b] Comparison among tillage systems CT-Sb, NT1-Sb, NT2-Sb and NT3-Sb; Lowercase letters within the same line indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 3.15

POC stocks (Mg ha^{-1}), on an equivalent soil-depth, in 0- to 100-cm soil depths under cassava-based cropping systems

Soil depth (cm)	RV[a*]	CT-Cs[b]	NT1-Cs	NT2-Cs	NT3-Cs
2011					
0–5	1.70 A	0.42 B ns	0.43 B	0.51 B	0.98 B
5–10	0.67 ns	0.47	0.43	0.58	0.43
10–20	0.70 ns	0.70	0.60	0.69	0.57
20–40	0.71 A	0.47 B ns	0.33 B	0.51 AB	0.29 B
40–60	0.38 A	0.22 B ns	0.18 B	0.17 B	0.20 B
60–80	0.24 ns	0.14	0.12	0.24	0.13
80–100	0.24 ns	0.19	0.16	0.28	0.33
0-100	4.64 A	2.61 B ns	2.25 B	2.98 B	2.93 B
2013					
0–5	1.70 A	0.55 Dc	0.82 CDbc	0.86 Cb	1.25 Aa
5–10	0.67 ns	0.62	0.59	0.69	0.68
10–20	0.70 ns	0.78	0.68	0.75	0.67
20–40	0.71 ns	0.52	0.39	0.54	0.50
40–60	0.38 A	0.27 B	0.22 B	0.21 B	0.24 B
60–80	0.24 ns	0.17	0.15	0.27	0.18
80–100	0.24 ns	0.21	0.18	0.31	0.31
0-100	4.64 A	3.12 Bns	3.03 B	3.63 B	3.83 AB

PE: prior to experiment establishment; RV: reference vegetation; CT: conventional tillage; NT: no-till; [a] Comparison between tillage systems CT-Sb, NT1-Cs, NT2-Cs, NT3-Cs and RV; Uppercase letters within the same line in each cropping system indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [*] RV collected in 2011 is used for both 2011 and 2013. [b] Comparison among tillage systems CT-Cs, NT1-Cs, NT2-Cs and NT3-Cs; Lowercase letters within the same line indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 3.16

MAOC stocks (Mg ha^{-1}), on an equivalent soil-depth, in 0- to 100-cm soil depths under cassava-based cropping systems in 2011

Soil depth (cm)	RV[a*]	CT-Cs[b]	NT1-Cs	NT2-Cs	NT3-Cs
0–5	12.01 A	6.87 B ns	6.76 B	7.57 B	7.20 B
5–10	9.47 A	7.27 B ns	6.95 B	7.56 B	7.08 B
10–20	13.69 ns	14.49	12.42	14.21	12.48
20–40	18.29 ns	19.56	15.68	17.12	14.78
40–60	11.91 ns	13.21	11.55	12.41	11.04
60–80	9.34 ns	9.93	9.20	10.28	8.78
80–100	9.07 ns	9.83	8.53	9.53	8.36
0-100	83.78 ns	81.16	71.09	78.68	69.72

PE: prior to experiment establishment; RV: reference vegetation; CT: conventional tillage; NT: no-till; [a] Comparison between tillage systems CT-Sb, NT1-Cs, NT2-Cs, NT3-Cs and RV; Uppercase letters within the same line in each cropping system indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [*] RV collected in 2011 is used for both 2011 and 2013. [b] Comparison among tillage systems CT-Cs, NT1-Cs, NT2-Cs and NT3-Cs; Lowercase letters within the same line indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

CHAPTER 4

Sensitivity of Labile Soil Organic Carbon Pools and Enzymatic Activities to Short-term Conservation Agriculture Cropping Systems

Abstract

Soil organic carbon (SOC) pools, particularly labile pools, and soil enzymes are good indicators of short-term impacts of soil management practices. The objective of this study was to investigate the sensitivity of the labile SOC pool (i.e., hot-water extractable C - HWEOC and permanganate oxidizable C - POXC) and soil enzyme activities (i.e., β-glucosidase, arylsulfatase) to changes in soil management and crop rotations with diverse crop residue inputs in rice-, soybean- and cassava-based cropping systems (RcCS, SbCS, and CsCS, respectively). The four treatments in each cropping system consisted of (a) conventional tillage (CT); (b) no-till (NT): one year frequency pattern of main crops; and (c) and (d) NT: bi-annual rotations of main crops with maize. The field trials were initiated in 2009 and the measurements of labile SOC pools were conducted in 2011 and 2013, and pyrophosphate extractable organic C (PEOC), chemically stabilized organic C (CSOC) and soil enzyme activities only in 2011. On average, the results showed greater HWEOC stocks by 61%, 55% and 53%, and POXC stocks by 23%, 21% and 32% in NT than in CT soils under RcCS, SbCS and CsCS, respectively, at 0-5 cm soil layer after five years. PEOC and CSOC stocks were almost constant in each depth among treatments, except 0-5 cm in CsCS. β-glucosidase activity was 18%, 28% and 49% greater in NT than in CT soils at 0-5 cm under RcCS, SbCS, CsCS, respectively, whereas arylsulfatase activity was 36% and 39% in NT than in CT under SbCS and CsCS, respectively, but no significant differences in RcCS. Compared among three NT treatments, bi-annual crop rotations showed a better increasing trend of HWEOC, POXC and enzymatic activities than one-year frequency pattern. In

conclusion, short-term NT crop rotations with permanent soil cover significantly increased the storage of HWEOC and POXC and enhanced β-glucosidase and arylsulfatase activities at the surface soil layer with a potential at the subsoil layers as a result of higher biomass-C inputs and the absence of soil disruption. Thus, the labile SOC pool and soil enzymes could be served as sensitive indicators of SOC dynamics to short-term changes in soil management and crop rotations.

4.1 Introduction

Soils can be either a sink for or a source of CO_2 depending on land use and management (Lal, 2003b, 2010). Changes in agricultural management practices might determine either function of soils due to their important contribution to the soil C sequestration process. In Cambodia, the development of annual upland crops (i.e., maize, cassava, soybean, and mungbean) to satisfy the needs of expanding population soared from ~ 217K ha in 2003 to ~ 716K ha in 2012 (MAFF, 2013). This leads to forest clearance to expand the agricultural land that has exacerbated the growing concern over land degradation (Belfield et al., 2013; Hean, 2004; Poffenberger, 2009; UNDP, 2010). The particular challenges to evaluate land productivity, to improve soil health and to sequester soil C are necessary to define sustainable agricultural practices in this country. Globally, there is a growing interest in development of agricultural management practices to sequester atmospheric CO_2 into soil C (Lal, 2008a) and the extent to which soils can sequester C varies with soil mineralogy, net primary production (Tivet, Sá, Lal, Borszowskei, et al., 2013), climate, cropping systems and tillage practices (Wright, Hons, Lemon, McFarland, & Nichols, 2008). Soil organic C (SOC) plays a crucial role in enhancing crop productivity (Lal, 2003b) as a result of its profound impacts on soil physical, chemical and biological properties (Ayuke et al., 2011; Lal, 2008b; Lienhard et al., 2013; Six et al., 2004;

Tisdall & Oades, 1982). Frequent conventional tillage (CT) hastens SOC mineralization due to greater exposure to microbial oxidation (Green et al., 2007; Jastrow, Boutton, & Miller, 1996; Reicosky et al., 1995) resulting from the breakdown of soil aggregates (Zotarelli et al., 2007) and marked changes in soil environment (i.e., temperature, moisture and oxygen), thus increasing soil microbial biomass and activity (D. Guo et al., 2013) and causing a drastic increase in C efflux from soil to the atmosphere (Lal & Logan, 1995). This SOC decline causes poor aggregation, acceleration in soil erosion, and reduced soil biological and enzymatic activities (Ghani et al., 2003).

SOC can be enhanced by crop rotations and no-tillage (NT) practices due to addition of biomass-C inputs into the soil via crop residues near the soil surface and the absence of soil disruption (Lal et al., 2003). Without massive supplies of organic materials, it is extremely difficult to sequester SOC in arable soils (Powlson et al., 2011). Conservation agriculture (CA) holds tremendous potential for sustainable soil management through the application of its three key principles: (a) continuous minimal mechanical soil disturbance (no-tillage), (b) permanent organic soil cover, and (c) diversified crop rotations grown in sequence or associations (FAO, 2008). The CA practices increase annual C inputs through plant roots, root exudates and aboveground plant residues, and decrease SOC decomposition rates through increased soil aggregation and a protection of SOC from decomposers. The impacts of CA or its different component practices have been reviewed as a set of improved agricultural practices to potentially sequester C into the soils in various regions (Corsi et al., 2012; Govaerts et al., 2009; Lal, 2006; Luo et al., 2010; Ogle et al., 2012).

To assess SOC dynamics under CA, several indicators of SOC pools and enzymatic activities have recently received more attention due to their sensitivity to soil management practices. The SOC pool is highly diverse with contrasting turnover times, and stabilized or protected against microbial decomposition (Lützow et al., 2006). A better understanding of the short-term impacts of CA on SOC dynamics necessitates separation of SOC into pools. Active or SOC labile pool might be potentially restored even in a short period because it is the most rapid turnover times and its oxidation drives the flux of CO_2 between soils and atmosphere. Its sensitivity better explains soil biological effects on soil properties and SOC dynamics compared with total SOC (Campbell et al., 1997; Z. Huang et al., 2008), thus serving as an indicator of future changes in total SOC (Campbell et al., 1997). Hot-water extractable organic C (HWEOC) is a sensitive indicator of SOC quality and constitutes the readily-decomposable SOM (Ghani et al., 2003). It responds rapidly to changes in C supply (Jinbo et al., 2006) and indicates the effect of land use on soil organic matter (SOM) quality (Gregorich, Monreal, Carter, Angers, & Ellert, 1994). The dissolved organic C, microbial biomass, soluble soil carbohydrates and amines are extracted from soil during the extraction of HWEOC (Ghani et al., 2003). Similarly, permanganate oxidizable carbon (POXC) is also an active SOC pool and correlates with soil microbial activity including soil microbial biomass C (SMBC), soluble carbohydrate C and total C (Weil et al., 2003). Positive relationships between SMBC and HWEOC (Ghani et al., 2003; Ghani et al., 2010; Sparling et al., 1998), between SMBC and POXC (Culman et al., 2010; Melero et al., 2009), and between SOC and labile pools (i.e., HWEOC and POXC) (Culman et al., 2012; Sá et al., 2014; Tirol-Padre & Ladha, 2004; Weil et al., 2003) have been reported. For example, the studies by Sá et al. (2014) in a subtropical region and by Tivet, Sá, Lal, Borszowskei, et al. (2013) in tropical and subtropical regions indicated a high potential of NT systems with cover crops to restore the labile SOC pool (i.e., HWEOC, POXC) in the soil surface layers. The increased labile SOC pool under NT cropping systems can be the pathway to sequester C from the atmosphere to soils and to decrease the release of SOC back to the atmosphere.

Soil enzymes play a substantial role in organic matter mineralization through a wide range of metabolic processes (María et al., 2002) and their activities are sensors of SOM decomposition in the soil system by providing information about microbial status and soil physicochemical conditions (Sinsabaugh et al., 2008). Sources of soil enzymes include living and dead microorganisms, plant roots and plant residues, and soil animals (Das & Varma, 2011). NT, high residue return and crop rotations have been reported to enhance enzymatic activities. Soil enzymes respond to soil management changes more quickly than other soil quality indicator changes and detection (Dick, 1994; Ndiaye et al., 2000). Arylsulfatase (EC 3.1.6.1) plays a role in S cycling and can catalyze the hydrolysis of organic sulfate esters (M. A. Tabatabai & Bremner, 1970). High organic C inputs via crop residues constitute a principal reservoir of sulfate esters, the substrate for arylsulfatase that involves in the mineralization of ester sulfate. (Dick et al., 1997). β-glucosidase (EC 3.2.1.21) plays a role in the C cycle and is closely related to the transformation and accumulation of SOM (Wang & Lu, 2006) because it is regarded as the most abundant extracellular enzyme in soil (Busto & Perez-Mateos, 2000). Green et al. (2007) found that β-glucosidase activity was greater in the soil under NT than that under disk plow in the tropical Savannah.

At tropical temperatures, SOM is broken down ten times faster, allowing for more rapid biomass growth but resulting in a smaller soil C pool compared with temperate climate (Malhi, Baldocchi, & Jarvis, 1999). Short-term changes in total SOC due to soil management practices are often difficult to detect (Zotarelli et al., 2007). However, the short-term effects of CA on labile SOC pool (i.e., HWEOC, POXC) and soil enzymatic activities remain debatable. The combination of labile SOC pool and enzymatic activities can provide valuable information to assess short-term SOC dynamics and the estimation over long-term trends. Thus, this study aimed to investigate the sensitivity of labile SOC pool and soil enzyme activities changes to soil management and crop rotations with diverse crop residue inputs in rice-, soybean- and cassava-based cropping systems.

4.2 Materials and Methods

Detailed descriptions of the site, experiments, biomass-C inputs and soil sampling are reported in Chapter 3. Briefly, the field experiments were initiated in 2009 in a Latosol at Bosknor Research Station in Kampong Cham Province, Cambodia (Latitude 12°12′30″N, longitude 105°19′7″E and 118 m elevation). The adjacent reference vegetation (RV) was located ~ 500 m from the experimental plots (latitude 12°12′13″N, longitude 105°19′11″E and 118 m elevation). The vegetation composition was the old coffee plantation under the shade of *Leucaena glauca* which was grown since 1990 and was selected as a baseline to assess the management-induced changes in SOC pools and enzymatic activities.

The experiments distinctly comprised of (a) rice- (b) soybean- and (c) cassava-based cropping systems (RcCS, SbCS, CsCS, respectively). The three-replicated experimental plots were laid out in randomized complete block design with four treatments in each cropping system consisting of (a) conventional tillage (CT) in which the main crops were planted in annual succession for rice and soybean (i.e., mungbean/rice–CT-Rc, sesame/soybean–CT-Sb) and mono-cropping for cassava (CT-Cs); (b) no-till (NT) in which main crops were planted in a one year frequency pattern (NT1-Rc, NT1-Sb, NT1-Cs); and (c) and (d) NT in which main crops were planted in bi-annual rotations with maize, the two plots in these bi-annual rotations being NT2-Rc, NT3-Rc for rice, NT2-Sb, NT3-Sb for soybean and NT2-Cs, NT3-Cs for cassava. Basal

P fertilizer application was done by surface banding with thermo phosphate (i.e., 16% P_2O_5, 31% CaO and 16% MgO), and fractioned top dressing on main crops for N and K, using urea (46 % N) and potassium chloride (60 % K_2O), respectively. The total fertilizer input (2009-2013) was 208 kg ha^{-1} P_2O_5, 253 kg ha^{-1} N, 180 kg ha^{-1} K_2O_5 for rice, 208 kg ha^{-1} P_2O_5, 115 kg ha^{-1} N, 300 kg ha^{-1} K_2O_5 for soybean, 208 kg ha^{-1} P_2O_5, 368 kg ha^{-1} N, 330 kg ha^{-1} K_2O_5 for cassava, and 208 kg ha^{-1} P_2O_5, 368 kg ha^{-1} N, 180 kg ha^{-1} K_2O_5 for maize. The aboveground biomass of main and cover crops were measured and the belowground biomass was estimated on the basis of the root to shoot ratio (RS ratio) index. The details of accumulative and annual biomass-C inputs (2009–2013) in each cropping system are presented in Table 4.1.

Soil samples at seven depths: 0-5, 5-10, 10-20, 20-40, 40-60, 60-80, and 80-100 cm were collected during November 2011 and 2013. Bulk samples were oven-dried at 40 ºC, gently ground, sieved through a 2-mm sieve and homogenized. Due to high clay content of the studied soil, it was assumed that the bulk density did not significantly change within this two-year period (2011-2013). Thus, soil bulk density (ρ_b) was measured only in 2011 and used to calculate PEOC and CSOC stocks in 2011, and HWEOC and POXC stocks in both 2011 and 2013 by computing on an equivalent soil mass-depth basis described by Ellert and Bettany (1995).

4.2.1 Soil organic C pool extraction and analysis. Different SOC pools were isolated by (a) hot-water extractable organic C (HWEOC), (b) permanganate oxidizable C (POXC), (c) (sodium) pyrosphospate extractable organic C (PEOC) and (d) the chemically stabilized organic C (CSOC) extracted by H_2O_2 oxidation. The analyses of HWEOC, POXC and PEOC were conducted in a sequence using the soil sample in the same tube.

4.2.1.1 Hot-water extractable organic C. The HWEOC was determined by the method adapted from Ghani et al. (2003). Briefly, 1.5 g of 2 mm-sieved bulk soil was weighed into a 15 mL polypropylene centrifuge tube. The sample was treated with 9 mL of distilled water for 16 hours at 80 ºC. Each tube was then shaken on a vortex shaker for 10 sec to ensure that the HWEOC released from the SOC was fully suspended in the solution. The tubes were centrifuged for 10 min at 4000 rpm. The SOC in the centrifuged extracts was oxidized by potassium dichromate in sulfuric acid and back titrated with ferrous sulfate.

4.2.1.2 Permanganate oxidizable C. The determination of POXC is adapted from Tirol-Padre and Ladha (2004) and Culman et al. (2012). After the extraction of HWEOC, the remaining supernatant in each tube was discarded and 10 mL of a stock solution of $KMnO_4$ (60 mM) was added to the sediments in the same tubes and shaken on a vortex shaker for 15 sec to suspend the soil in the stock solution. The tubes were horizontally shaken on a table shaker at 200 rpm for 15 min at room temperature, and then centrifuged for 10 min at 4000 rpm. 2 mL of the supernatant was pipetted and transferred to a 125 mL Erlenmeyer flask and diluted with 100 mL deionized water. The absorbance of the solutions was determined at 565 nm using Visible Spectrophotometer (SP-1105), and the amount of the oxidized organic C was calculated from the $KMnO_4$ consumed. The conversion of the absorbance to POXC concentration (g kg^{-1}) was done by using a standard calibration curve, based on the linear relationship between $KMnO_4$ concentrations vs. absorbance at 565 nm. The amount of POXC was computed as follow:

$$POXC\ (g\ kg^{-1}) = [(mM\ blank - mM\ sample) \times (125/2) \times 10 \times 9] / [1000\ (mL\ L^{-1}) \times wt\ of\ sample\ (g)]$$

Where, mM blank and mM sample are the concentrations (mmol L^{-1}) of $KMnO_4$ in the blank and sample, respectively, determined from the standard regression curve; 125/2 = the dilution factor (mL mL^{-1}); 10 = the volume (mL) of $KMnO_4$ added to the soil sample; 9 = the amount of C oxidized from every mole of $KMnO_4$ (g mol^{-1} or mg $mmol^{-1}$).

4.2.1.3 (Sodium) Pyrophosphate extractable organic C. The determination of PEOC is adapted from Bascomb (1968) and McKeague, Brydon, and Miles (1971), using only the samples collected in 2011. After removal of the $KMnO_4$ supernatant, the $KMnO_4$ residue in the sediments was washed out with deionized water for 3-4 times. Then, a third extraction was performed by adding 10 mL of 0.1 M sodium pyrophosphate ($Na_4P_2O_7$) solution into the same tubes and shaken on a vortex shaker for 15 sec to suspend the soil in the solution. The tubes were horizontally shaken on a table shaker at 120 rpm for 6 hours at room temperature, and then centrifuged for 10 min at 4000 rpm. The SOC in the centrifuged extracts was oxidized by potassium dichromate in sulfuric acid and back titrated with ferrous sulfate. The SOC dissolved in the pyrophosphate extract corresponds to the SOC associated with the active forms of Al and Fe.

4.2.1.4 Chemically stabilized organic C. The determination of CSOC was based on the method by Jagadamma, Lal, Ussiri, Trumbore, and Mestelan (2010) using only the samples collected in 2011. Briefly, 1 g of bulk soil was wetted with 10 mL of distilled water for 10 min. Then, 30 mL of H_2O_2 at 10% was added, and the solution was kept at 50 ºC using a water bath. Each sample was manually shaken daily to ensure a good oxidation, and additional H_2O_2 was added if necessary. The oxidation period, using H_2O_2 as the oxidizing agent, requires several days and depends on texture, mineralogy, the pre-existing SOC concentration, and the nature and quantity of the C inputs. The oxidation was stopped when the frothing completely subsided. The sample was then washed thrice with 30 mL distilled water and oven-dried at 40 ºC until constant weight. The sample weight was recorded. The sample was finely ground for C determination by the dry combustion method using an elemental CN analyzer (TruSpec CN, LECO, St. Joseph, USA).

4.2.2 Assay of soil enzyme activities. The soil enzyme activities were measured at three soil depths, 0–5, 5–10 and 10–20 cm using the same composite soil samples used to analyze SOC pools.

4.2.2.1 β-glucosidase. Activity of *β*-glucosidase (EC 3.2.1.21, β-d-glucoside glucohydrolase) was assayed according to the method of Eivazi and Tabatabai (1988). Briefly, 1 g of dry soil (< 2 mm) was placed into a 50 mL flask, and then 4 mL of pH 6.0 of modified universal buffer (MUB) and 1 mL of 0.05 M *p*-nitrophenyl-*β*-D-glucoside (PNG) solution were added. The flask was swirled to fully mix the contents, stoppered, and incubated at 37 ºC for 1 hour. Then, 1 mL of 0.5 M $CaCl_2$ and 4 mL of 0.1 M pH 12 tris (hydroxymethyl) aminomethane (THAM) buffer were added to stop the reaction. The soil suspension was allowed to develop a yellow color and filtered. The color intensity was determined using a spectrophotometer at 400 nm. *β*-glucosidase activity was reported on a dry soil basis with units of mg *p*-nitrophenol kg^{-1} soil h^{-1}.

4.2.2.2 Arylsulfatase. Arylsulfatase (EC 3.1.6.1., arylsufate sulfohydrolase) activity was assayed according to the method of M. A. Tabatabai and Bremner (1970). Briefly, 1 g of dry soil (< 2 mm) was placed into a 50 mL flask, and incubated with 4 mL of 0.5 M acetate buffer (pH 5.8) and 1 mL of 0.05 M *p*-nitrophenol (PN) sulfate solution at 37 ºC for 1 hour. Then, 1 mL of 0.5 M $CaCl_2$ and 4 mL of 0.5 M pH 12 NaOH were added to stop the reaction. The PN released was extracted and filtered, and the color intensity was determined using a spectrophotometer at 400 nm. Arylsulfatase activity was quantified as mass (mg) of *p*-nitrophenol being produced by enzymatic hydrolysis of potassium *p*-nitrophenyl sulfate during 1 hour incubation per unit mass (kg dry soil; PNP equivalents).

4.2.3 Statistical analysis. The statistical analysis was performed using SAS 9.2 statistical software. To compare the effects of tillage and crop sequence treatments of cropping system at each depth, data were independently subjected to analysis of variance procedures with randomized complete block design, and comparisons among treatment means were calculated based on least significant difference test (LSD) at the 0.05 probability level, unless otherwise stated.

4.3 Results

4.3.1 Soil organic C pools (HWEOC, POXC, PEOC, CSOC).

4.3.1.1 Rice-based cropping systems. Tillage and crop rotation treatments had a significant ($P<0.05$) effect on HWEOC concentrations at the 0-5 cm soil layer in 2013 (Figure 4.1b). The increasing trend of higher accumulation was observed in 2011, in which soils under NT averagely had 12% more HWEOC concentrations at 0-5 cm and the bi-annual crop rotations (NT2-Rc and NT3-Rc) tended to accumulate more than NT1-Rc. In the subsoil layers, the differences were not evident among treatments. In 2013, soil under NT1-Rc, NT2-Rc, and NT3-Rc contained 46%, 60%, and 76%, respectively, greater HWEOC concentrations than CT-Rc at 0-5 cm soil depth. The increasing trend was also observed at 5-10 cm depth. On an average, NT-Rc soils had 42% more HWEOC than CT-Rc soil. Significant effects of tillage and crop rotation treatments on HWEOC stocks were detected at 0-5 cm depth in both 2011 and 2013 ($P<0.05$) (Table 4.2). In 2011, HWEOC stocks under NT3-Rc were significantly greater than that under CT-Rc, but not those under NT1-Rc and NT2-Rc. On average in 2013, NT-Rc soils contained 61% higher than CT-Rc. There was a consistent increase in HWEOC stocks in the three NT treatments until 20 cm soil depth but a decrease in CT-Rc. The RV soil had significantly higher HWEOC stocks than cultivated soils (i.e., NT-Rc, CT-Rc) at 0-5 and 5-10 cm depths in 2011 but only 0-5 cm depth in 2013. Soil under RV contained 69%, 63%, 44%, and 40% higher HWEOC stocks than CT-Rc, NT1-Rc, NT2-Rc, and NT3-Rc, respectively, at 0-5 cm in 2011. At 5-10 cm, RV also had 48% and 39% greater HWEOC than CT-Rc and NT-Rc (i.e., NT1-Rc, NT2-Rc, NT3-Rc). In 2013, soil under RV had 96% and 21% higher HWEOC stocks than those under CT-Rc and NT-Rc, respectively, at 0-5 cm depth. Considering the 100 cm as a single stratum, HWEOC stocks under RV were significantly greater than under cultivated soils in 2011 but not in 2013 while no significant differences were detected among NT-Rc and CT-Rc. On average, NT-Rc had 10% and 20% more HWEOC stocks in 2011 and 2013, respectively, compared with CT-Rc.

NT-Rc significantly increased POXC concentrations and stocks at 0-5, 40-60 and 60-80 and 80-100 cm depths in 2011 and only 0-5 cm depth in 2013 (Figure 4.1). In 2011, POXC concentration in soils under NT-Rc was 14% greater than that under CT-Rc. The noticeable increasing trend also appeared at 5-10 cm depth, at which soils under NT-Rc had 11% higher POXC. In 2013, soils under NT1-Rc, NT2-Rc, and NT3-Rc had 18%, 21%, and 24%, respectively, significantly higher POXC concentrations than under CT-Rc at 0-5 cm depth. POXC tended to increase in all treatments at 0-20 cm depths interval from 2011 to 2013. The CT-Rc soil contained lower POXC stocks of 0.15 Mg ha^{-1} in 2011 and 0.23 Mg ha^{-1} in 2013 than NT-Rc soils at 0-5 cm depth (Table 4.3). The same trend was observed 5-10 and 10-20 soil depths. NT-Rc resulted in a higher trend of increasing POXC stocks in the subsoil layers compared with CT-Rc in 2013. POXC stocks under RV were 0.62 and 0.47 Mg ha^{-1} at 0-5 cm and 0.31 and 0.20 Mg ha^{-1} at 5-10 cm greater than under CT-Rc and NT-Rc, respectively, in 2011. As a result of increased biomass-C inputs, the differences decreased by 5% and 20% at 0-5 cm, and by 8% and 13% at 5-10 cm depth under CT-Rc and NT-Rc in 2013, respectively.

Considering the 100 cm as a single stratum, NT-Rc soils reserved 7% and 14% more POXC stocks than that of CT-Rc in 2011 and 2013, respectively. Comparing to RV, POXC stocks under NT-Rc, particularly bi-annual rotations, showed a surpassing trend over that under RV in 2013.

Differences in tillage and crop rotations did not significantly affect the changes in concentrations and stocks of PEOC and CSOC in all depths (Figure 4.1a and Table 4.4). Although, they did not differ, the increasing trend of PEOC concentrations was observed in bi-annual crop rotations compared with CT-Rc. On average, they accumulated 6% at 0-5 cm and 7% at 5-10 cm depth higher PEOC than CT-Rc soil. Unlike PEOC, CT-Rc soil contained more CSOC concentrations in most depths compared with NT-Rc soils. At 0-5 and 5-10 cm depths, soils under CT-Rc had 13% and 9%, respectively, more CSOC concentrations than under NT-Rc. PEOC stocks in all treatments were almost constant in all depths but significantly lower than those under RV. Soils under RV significantly stored 70%, 41%, 45%, and 29% greater PEOC stocks than cultivated soils at 0-5, 5-10, 10-20, and 20-40 cm depths, respectively. In contrast to PEOC, significant differences in CSOC between RV and cultivated soils were not detected. Soils under CT-Rc tended to store more CSOC in the two surface layers. Considering the 100 cm as a single stratum, RV soil had 4.0 and 1.17 Mg ha^{-1} more PEOC and CSOC stocks than cultivated soils, respectively. Overall, the mean portions of the SOC pools for RV and treatments and depths ranged in the order CSOC > POXC > PEOC > HWEOC.

4.3.1.2 Soybean-based cropping systems. Significant ($P < 0.05$) effects of tillage and crop rotations on HWEOC concentrations were detected at the 0-5 cm depth in 2013 (Figure 4.2b). On average, bi-annual rotations (NT2-Sb and NT3-Sb) contained 16% more HWEOC than CT-Sb soil while only 3% under NT1-Sb at 0-5 cm depth in 2011. In 2013, HWEOC concentrations were higher by 52%, 50%, and 64% under NT1-Sb, NT2-Sb, and NT3-Sb, respectively, compared with that under CT-Sb at 0-5 cm depth. An increasing trend was also observed at 5-10 cm depth. There was no clear evidence of significant differences in the subsoil layers in both 2011 and 2013. The significant differences in HWEOC stocks were detected at 5-10 cm depth in 2011 (P < 0.05) and 0-5 cm depth in 2013 (P < 0.05) (Table 4.5). Although they did not differ at 0-5 cm depth in 2011, NT-Sb (NT1-Sb, NT2-Sb, NT3-Sb) tended to store 12% higher HWEOC than that of CT-Sb. This increasing trend was apparent in 2013. On average, HWEOC stocks under NT-Sb were 55% (0.15 Mg ha^{-1}) greater than that under CT-Sb. From 2011 to 2013, HWEOC stocks decreased by 7% under CT-Sb but increased by 29% under NT-Sb. When comparing to RV, HWEOC stocks under RV were greater than CT-Sb and NT-Sb by 63% and 46% at 0-5 cm, and by 48% and 52% at 5-10 cm depth, respectively, in 2011. This trend was changed in 2013, in which the differences were increased by 12% in CT-Sb but decreased 33% in NT-Sb. Considering the 100 cm as a single stratum, there were no significant differences in HWEOC stocks between RV and cultivated soils (i.e., CT-Sb, NT-Sb). However, bio-annual crop rotation treatments tended to increase more HEWOC than CT-Sb.

Differences in tillage and crop rotations resulted in significant changes in POXC concentrations at 0-5 cm depth in 2011, and at 0-5 and 10-20 cm depths in 2013 (Figure 4.2). Soil under NT3-Sb accumulated 19% greater POXC than that under CT-Sb. Although they did not differ, soils under NT1-Sb and NT2-Sb quantitatively had 11% and 14% more POXC than that under CT-Sb. The increasing trend was evident in 2013, in which POXC concentrations under NT-Sb soils were 21% higher than CT-Sb. There were no noticeable variations in the deeper soil layers in both 2011 and 2013. In general, POXC stocks showed no significant differences among treatments at most depths except 60-80 cm in 2011, and 0-5 and 10-20 cm in 2013 (Table 4.6). The trend of increasing POXC stocks under NT-Sb was still observed at 0-5 cm depth in 2011. On average, NT-Sb soils stored 14% more POXC than CT-Sb. In 2013, NT-Sb had 21% greater POXC stocks than CT-Sb. Similar trend was also found at 10-20 cm depth. When comparing to RV, soils under RV had greater POXC stocks than under CT-Sb and NT-Sb by 54% and 35% in 2011, and 54% and 27% in 2013, respectively, at 0-5 cm depth. Considering the 100 cm as a single stratum, POXC stocks were almost constant among RV and cultivated soils in 2011. However, significant differences were detected in 2013 but RV did not differ from NT-Sb.

Similar to RcCS, no significant differences in PEOC and CSOC concentrations and stocks were detected after three years (Figure 4.2a and Table 4.7). The average PEOC concentration under NT-Sb soils was 2.75 g kg^{-1} which was 4% more than that under CT-Sb. The concentrations decreased with increasing depths but there was no clear evidence of the differences or even an increasing trend in the subsoil layers. Similarly, both CT-Sb and NT-Sb soils showed constant CSOC concentrations in each depth and it ranged from 5.15 to 5.29 g kg^{-1} at 0-5 cm depth and 3.42 to 3.85 g kg^{-1} at 80-100 cm depth. RV soils significantly had 39% greater PEOC stocks than cultivated soils only at 0-5 cm depth. In contrast, RV and cultivated soils had no significant differences in CSOC stocks at all depths. Considering the 100 cm as a single stratum, PEOC and CSOC stocks did not differ between RV and cultivated soils.

4.3.1.3 Cassava-based cropping systems. Significant effects of tillage and crop rotations on HWEOC concentrations and stocks were detected at only 0-5 cm depth in both 2011 and 2013 ($P < 0.01$ and $P < 0.05$, respectively; Figure 4.3 and Table 4.8). On average, the bi-annual crop rotation treatments (NT2-Cs and NT3-Cs) accumulated 17% higher HWEOC concentrations than CT-Cs in 2011 and it increased to 58% in 2013 at the 0-5 cm depth. The significant increase also observed in NT1-Cs which had 42% greater HWEOC than CT-Cs at 0-5 cm depth in 2013. Soils under CT-Cs showed a decrease in HWEOC concentration by 12% at 0-5 cm and 9% at 5-10 cm depth from 2011 to 2013. However, there were noticeable changes in the deeper soil layers among the treatments. HWEOC stocks under NT-Cs (i.e., NT1-Cs, NT2-Cs, NT3-Cs) averagely increased 20% from 2011 to 2013. Soils under RV had greater HWEOC than CT-Cs and NT-Cs by 69% and 48% in 2011, and 88% and 24% in 2013, respectively. Considering the 100 cm as a single stratum, RV and cultivated soils (i.e., CT-Cs, NT-Cs) did not significantly differ in both sampling times. The increase in HWEOC was observed in NT-Cs. The stocks ranged in the order RV > NT-Cs > CT-Cs.

The differences in tillage and crop rotations resulted in significant effects on POXC concentrations and stocks at 0-5, 40-60, 60-80 and 80-100 cm depths in 2011, and only 0-5 cm depth in 2013 (Figure 4.3 and Table 4.9). On average, the bi-annual rotations accumulated 18% and 15% higher POXC than CT-Cs and NT1-Cs soils, respectively, in 2011 and the differences increased to 40% for CT-Cs and 25% for NT1-Cs in 2013. Similar to the surface 0-5 cm, NT2-Cs and NT3-Cs showed a greater accumulation of POXC in the 40-100 depths interval in 2011 and their increasing trend was observed in the subsoil layers in 2013. From 2011 to 2013, POXC stocks increased 5%, 11% and 18% under NT1-Cs, NT2-Cs, and NT3-Cs, respectively, at 0-5 cm depth. In contrast, 4% decrease was observed in soil under CT-Cs. However, there were no noticeable changes in POXC stocks in the subsoil layers. At 0-5 cm depth, RV soils stored significantly higher POXC by 70%, 65%, 42%, and 46% under CT-Cs, NT1-Cs, NT2-Cs, and NT3-Cs, respectively, in 2011. The adoption of NT systems increased POXC stocks in 2013 by decreasing the differences by 8%, 14%, and 22% under NT1-Cs, NT2-Cs, and NT3-Cs, respectively; at 0-5 cm depth compared with those under RV in 2011, but 7% depletion of POXC was observed in CT-Cs. Considering the 100 cm as a single stratum, significant differences in

POXC stocks were detected in 2011. The soils under RV and bi-annual crop rotations treatments stored 11% and 8%, respectively, significantly greater than CT-Cs. In 2013, RV and NT-Cs soils still showed an increasing trend compared to CT-Cs.

PEOC concentrations and stocks were influenced by tillage and crop rotations at 0-5 cm depth but the significant differences in CSOC concentrations and stocks were not detected in all soil depths (Figure 4.3a and Table 4.10). PEOC concentrations under bi-annual rotations were 12% and 7% greater than those under CT-Cs and NT1-Cs, respectively, at 0-5 cm depth. An increasing trend under NT-Cs was also observed at 5-40 cm depths interval. RV soils had greater PEOC stocks than CT-Cs, NT1-Cs, NT2-Cs, and NT3-Cs by 62%, 55%, 44%, and 44% at 0-5 cm, and by 25%, 22%, 14%, and 11% at 5-10 cm depth, respectively. The different trend of PEOC under RV and treated soils was not apparent in the deeper soil layers. Similar to RcCS and SbCS, CSOC concentrations and stocks were nearly constant among treatments in all depths. Considering the 100 cm as a single stratum, PEOC and CSOC stocks were almost constant between RV and cultivated soils. It indicated that short-term NT with different crop rotations did not alter the changes in PEOC and CSOC in 100 cm soil depth.

4.3.2 Soil enzyme activities (β-glucosidase and arylsulfatase).

4.3.2.1 Rice-based cropping systems. β-glucosidase activity was significantly influenced by tillage and crop rotations at 0-5 cm depth, with the average of NT-Rc being 18% greater than CT-Rc while there were no significant differences in the subsoil layers. In contrast, arylsulfatase activity was not found to be significantly different at all depths after three years (Table 4.11). However, the increasing trend of arylsulfatase activity under NT-Rc soils was observed at 0-5 cm depth, at which NT-Rc tended to have 5% greater than CT-Rc. The surpassing trend of the two enzyme activities under NT-Rc over CT-Rc at 5-10 and 10-20 cm depths was not apparent.

When comparing to RV, β-glucosidase activity under RV soils was greater than CT-Rc, NT1-Rc, NT2-Rc, and NT3-Rc by 158%, 124%, 119%, and 115%, respectively, at 0-5 cm depth while it was greater by 80% and 72% under CT-Rc and NT-Rc soils at 5-10 cm depth. Similarly, arylsulfatase activity under RV soil was 63% and 57% greater than cultivated soils at 0-5 and 5-10 cm depths, respectively. Even with greater β-glucosidase and arylsulfatase activities in two surface layers under RV, no significant differences were detected at 10-20 cm depth.

4.3.2.2 Soybean-based cropping systems. β-glucosidase and arylsulfatase activities were significantly increased by NT-Sb compared with CT-Sb at 0-5 cm depth (Table 4.12). β-glucosidase activity under bi-annual crop rotation treatments (NT2-Sb and NT3-Sb) was 31% greater than CT-Sb. Its activity under CT-Sb and NT1-Sb did not significantly differ. However, NT1-Sb showed an increasing trend of 22% higher activity than CT-Sb. Similarly, average arylsulfatase activity under NT2-Sb and NT3-Sb was 46% greater than under CT-Sb while the increasing trend was apparent in NT1-Sb. The two enzymes activities were almost constant in the two subsoil layers. When comparing to RV, β-glucosidase activity under RV was significantly greater than under CT-Sb and NT-Sb by 174% and 114% at 0-5 cm, by 75% and 74% at 5-10 cm, and by 18% and 19% at 10-20 cm depth, respectively. Similarly, arylsulfatase activity was also found to be significantly different from CT-Sb and NT-Sb soils by 102% and 48% at 0-5 cm, and by 55% and 46% at 5-10 cm depth, respectively.

4.3.2.3 Cassava-based cropping systems. Significant effects of tillage and crop rotations on β-glucosidase and arylsulfatase activities were detected only at 0-5 cm depth, with β-glucosidase activity under NT2-Cs and NT3-Cs being 54% and 60%, and with arylsulfatase activity being 47% and 49%, respectively, greater than those under CT-Cs (Table 4.13). The increasing trend of β-glucosidase activity under NT-Cs soils was observed at 5-10 cm depth but not arylsulfatase activity. The activities of two enzymes were almost constant at the 10-20 cm depth. When comparing to RV, β-glucosidase activity under RV was greater than those under CT-Cs and NT-Cs by 241% and 130% at 0-5 cm, and by 106% and 67% at 5-10 cm, respectively. Similarly, arylsulfatase activity under RV was also greater than those under CT-Cs and NT-Cs by 138% and 71% at 0-5 cm, and by 61% and 46% at 5-10 cm depth, respectively. Even with greater enzymatic activities in the two surface layers, no significant differences were observed between RV and treated soils at 10-20 cm depth.

4.4 Discussion

4.4.1 Changes in hot-water extractable organic C, permanganate oxidizable C, pyrophosphate extractable organic C, and chemically stabilized organic C. HWEOC is representative of SMBC, containing more microbial-derived than acid hydrolysable carbohydrates (Haynes & Francis, 1993). Later, this finding was confirmed by some studies including those by Ghani et al. (2003) and Sparling et al. (1998) who emphasized positive correlation between SMBC and HWEOC. In addition, SMBC is also correlated well with POXC (Melero et al., 2009; Weil et al., 2003). Labile SOC pool is sensitive to changes in soil management practices so it can be served as an indicator to short-term impacts of agricultural management practices (i.e., NT cropping systems with cover crops). In the present study, HWEOC and POXC were able to differentiate the impact of short-term NT cropping systems. We observed a significant increase in HWEOC and POXC stocks after five years of the three intensive NT crop rotations with diversified cover crops in the surface soil layer in the three cropping systems. The possible contributing factor could be the continuous supply of biomass-C in the NT systems that might influence an increase in these two labile SOC pools due to higher aboveground and root inputs with enhanced crop intensity than CT that could stimulate of microbial activity (Lienhard et al., 2013). The increase in HWEOC could contribute to the changes in SOC due to its positive correlation with SOC (Sparling et al., 1998). CT practices decreased HWEOC stocks in the topsoil by 14%, 7% and 1% in RcCS, SbCS and CsCS, respectively, in two years (2011-2013; see Table 4.8). Explanations for this result may include less biomass-C inputs via crop residues under CT compared with NT, thus decreasing the supply of carbohydrates for microorganisms and soil enzyme activity resulting in a reduction in SMBC which correlates with HWEOC. Our finding contradicts the study by Salinas-Garcia et al. (2000) who indicated that the greater concentration of SMBC under NT practices than under CT resulted from higher accumulation of crop residues at the soil surface after six years in a dry tropical region of Mexico. Rhizodeposition of root mass and exudates greatly influences C turnover in soils (Kuzyakov, Ehrensberger, & Stahr, 2001) that could affect the net accumulation of HWEOC in soil rhizosphere (Ghani et al., 2003). In general, an increasing trend of HWEOC accumulation in the a few subsurface layers under NT was observed compared with CT. This was probably due to the incorporation of deep-rooted cover crops such as Congo grass, millet, sorghum, and sunhemp into crop rotations under NT practices in the three cropping systems. Continuous input of root biomass and exudates from these cover crops could contribute to the increase in HWEOC. Séguy et al. (2006) reported that SOC in the subsoil could be sequestered by higher SOC rhizodeposition of the deep rooting systems such as Congo grass and sorghum and *Crotalaria spp*. Similarly, intensive NT cropping systems also significantly increased POXC. Soils under NT averagely had 20%, 21%, and 32% greater POXC stocks than those obtained in CT at the 0-5 cm depth under RcCS, SbCS, and CsCS, respectively, after five years. This was probably the fact that accumulation of POXC results from the rate of biomass-C inputs from crop biomass, a major source of SOC, returned to the soil and the absence of soil disturbance under NT that reduced SOC mineralization. Even three years longer but in the similar soil type and climatic condition, these results are consistent with the study by Tivet, Sá, Lal, Borszowskei, et al. (2013) who reported a significantly increased HWEOC at 0-5 cm soil depth after eight-year intensive NT systems (e.g., diversity of cover/relay crops and high annual biomass input). Similar effects was also observed in the study by Stine and Weil (2002) in a tropical region of south central Honduras who found POXC was highly correlated to SOC and soils under NT contained grater POXC than CT emphasizing that changes in SOC resulted from proportional changes in both active and passive C fractions. Soil aggregate stability positively correlates to residue restitution and fungal and bacterial densities under NT systems (Lienhard et al., 2013), HWEOC (Haynes & Swift, 1990) and POXC (Stine & Weil, 2002). Thus, the greater HWEOC and POXC under NT systems maybe consequently enhance soil aggregate formation which may protect SOC (Tivet, Sá, Lal, Briedis, et al., 2013). The consistent effect of NT crop rotations with cover crops on HWEOC and POXC, after five years of management suggests that this this labile SOC pool (i.e., HWEOC, POXC) may be useful in assessing SOC dynamics of short-term changes in soil management practices, particularly the soil surface layer.

Pyrophosphate has been used to extract soil C due to its selective ability to remove Fe and Al-bound organic matter by complexing with di- and trivalent cations (Wattel-Koekkoek et al., 2001). Thus, PEOC pool represents the SOC associated with the active forms of Fe and Al. In the present study, PEOC were almost constant in each depth among treatments in RcCS and SbCS. However, it showed an increase under bi-annual crop rotations treatments at 0-5 cm depth in CsCS. The PEOC stocks averagely comprised of 16% of SOC stocks in 2011 (data not shown) and were comparable to POXC stocks in all cropping systems, demonstrating a potential of this clayed Cambodian Oxisol to function as a sink for SOC that could be related to the formation of complexes with the active forms of Fe and Al. Erich, Plante, Fernández, Mallory, and Ohno (2012) reported that PEOC likely represented the material that was chemically sorbed to soil surfaces and protected from decomposition due to this sorption. CSOC also known as the passive or refractory SOM pool is organic substances which is resistant to further mineralization (Eusterhues et al., 2005). Our results indicated that CSOC was almost constant among treatments at each soil layer. The CSOC concentrations ranged from 3.22 to 5.98 g kg^{-1}, 3.42 to 5.29 g kg^{-1} and 3.37 to 5.24 g kg^{-1} in RcCS, SbCS, and CsCS, respectively. These results of CSOC concentrations were in the ranges reported by Tivet, Sá, Lal, Borszowskei, et al. (2013) in a subtropical Oxisol and a tropical Latosol and by Eusterhues et al. (2005) in the temperate Cambisol and Podzol. This finding could be explained that the amount of young plant residue-derived SOC added to the soil from crop residues within three years did not affect CSOC, suggesting that CSOC in the C baseline could be related to chemical and morphological structure of SOM and chemical and physical nature of the soil minerals. The high clay contents of soils used in the present study were almost constant in each depth in the three cropping systems (Hok et al., under review). Clay minerals have a high specific surface area and carry a charge enabling them to bind, and thereby chemically stabilize SOM (Wattel-Koekkoek et al., 2001). The study of peroxide oxidation of clay-associated organic matter by Plante, Chenu, Balabane, Mariotti, and Righi (2004) found that there was no relationship between the proportion of hydrogen peroxide-resistant SOM and C depletion in a cultivation chronosequence. In general, our results showed a slight decrease with increasing depths in the three cropping systems. The slightly higher CSOC in the surface layers in this study was probably due to the fresh aliphatic plant materials resistant to H_2O_2 oxidation (Eusterhues et al., 2005) because the oxidation process was done with the bulk soil without prior removal of the labile SOC pool.

4.4.2 Changes in β-glucosidase and arylsulfatase. The enzyme activities in soil systems vary primarily due to different amounts of organic matter content and composition, living organisms' activity and intensity of biological processes (Das & Varma, 2011). They are sensitive indicators providing information on the impact of land use management and cropping systems (Fernandes et al., 2005; Rabary et al., 2008). In the present study, it is consistent that tillage and crop rotations only affected β-glucosidase activity in the surface soil layer when NT had 18%, 28%, and 49% higher than CT in RcCS, SbCS, and CsCS, respectively. This could be explained by the fact that biomass-C supplies from crop residues contained the readily available substrate such as carbohydrate that could increase this enzyme activity. Roldán et al. (2003) found that β-glucosidase is stimulated where crop residues are left intact on the soil surface. This result confirms the previous investigation that direct seeding mulch-based cropping systems with living much and crop residue significantly increased β-glucosidase activity (on average 121% greater) compared with CT systems at 0-5 cm soil depth over a 12-year period in a cold tropical climate of Madagascar (Rabary et al., 2008). A similar finding was also observed by Green et al. (2007) who found that the β-glucosidase activity in the soil under a NT corn-common bean rotation was 82% significantly greater than under disk plow management in the 0-5 cm depth after five-year NT practices in a red Latosol in the tropical Savannah. Our results also showed a decrease in β-glucosidase activity with increasing depths where NT systems mostly maintained an increasing trend over CT, except under NT3-Cs which was already significantly greater than that obtained in the CT-Cs. Although the residues were not mechanically incorporated with the soil, the restitution of crop residues on the soil surface led to a slow incorporation of organic materials into the soil. Together with root biomass and exudates, the significant increase in β-glucosidase activity in the subsoil layers might be apparent with longer time. Thus, NT cropping systems with permanent soil cover provide a good potential to enhance β-glucosidase activity not only in the top soil but also in the subsoil layers as the results of increasing trend was already observed in this study.

High biomass-C inputs constitute a principal reservoir of sulfate esters, the substrate for arylsulfatase (Dick et al., 1997), the enzyme being involved in mineralization of ester sulfate in the soil (M .A. Tabatabai, 1994). In the present study, NT practices maintained greater arylsulfatase activity in the surface layer in SbCS and CsCS. Although they did not differ in RcCS, NT still showed an increasing trend of 5% compared to CT. This greater arylsulfatase activity might result from the increase of SMBC from the higher crop residues under NT systems due to its relations to an increase in HWEOC and POXC. High organic matter inputs via crop residues tend to increase SMBC due to continuous provision of energy sources for microorganisms (Vaughan & Ord, 1985). The microbial biomass consists mostly of bacteria and fungi. Fungi and bacteria have about 42% and 10%, respectively, of its S as ester sulfate, the substrate for arylsulfatase (Saggar, Bettany, & Stewart, 1981). Some previous studies found a strong positive correlation between SMBC and arylsulfatase activity (Ekenler & Tabatabai, 2003; Gajda et al., 2013; Li & Sarah, 2003). In contrast to the result of this study, Green et al. (2007) who reported that there was no significant changes in arylsulfatase activity under five-year NT systems compared to disk plow systems in tropical Savannah. This was probably due to low biomass-C inputs since their study was conducted in a corn-common bean rotation without incorporation of other forage crops as soil cover unlike our study. However, the study in temperate soils by Gajda et al. (2013) indicated that arylsulfatase activity under eight-year NT systems was two- to threefold greater than that obtained under traditional tillage at 0-15 cm soil layer as a result of higher organic C inputs via plant residues. The significant effect of NT crop rotations with diversified cover crops on β-glucosidase and arylsulfatase activities in this study suggests that the two enzymes are good indicators to assess the effect of short-term NT crop rotations on the biological activity of soil, particularly the soil surface layer.

4.5 Conclusions

Short-term intensive NT cropping systems with permanent soil cover are likely to play a substantial role in increasing the storage of HWEOC and POXC and improving β-glucosidase and arylsulfatase activities, especially at the 0-5 cm soil layer. When comparing among NT systems, bi-annual crop rotations might be recommended as an appropriate crop rotation scheme in the studied soil type. The size of SOC pools and enzymatic activities decrease with increasing depths. These results emphasize the positive impact of the absence of soil disturbance under NT and the importance of the cover crops and their residues cropped in association or rotations with main crops to significantly accumulate more labile SOC pools and change the biological functioning of the soil, with higher soil enzyme activities in the surface layers. The increase in the two SOC pools might lead to increase soil aggregate stability that physically protects SOC and consequently to sequester total SOC. Incorporation of deep-rooting cover crops into crop rotation might be evident with time to potentially enhance the labile SOC pools and enzymatic activities in the subsoil layers. Thus, these two SOC pools and soil enzymes could serve as sensitive indices of management effects on SOC dynamics of short-term changes in agricultural management practices. Unlike labile SOC pool and soil enzymes, PEOC and CSOC were almost constant in each depth among treatments indicating that these two SOC pools might not be affected by short-term changes in soil management practices in the studied soil type. However, their applicability to other soil types, climatic conditions and agricultural management practices must be evaluated.

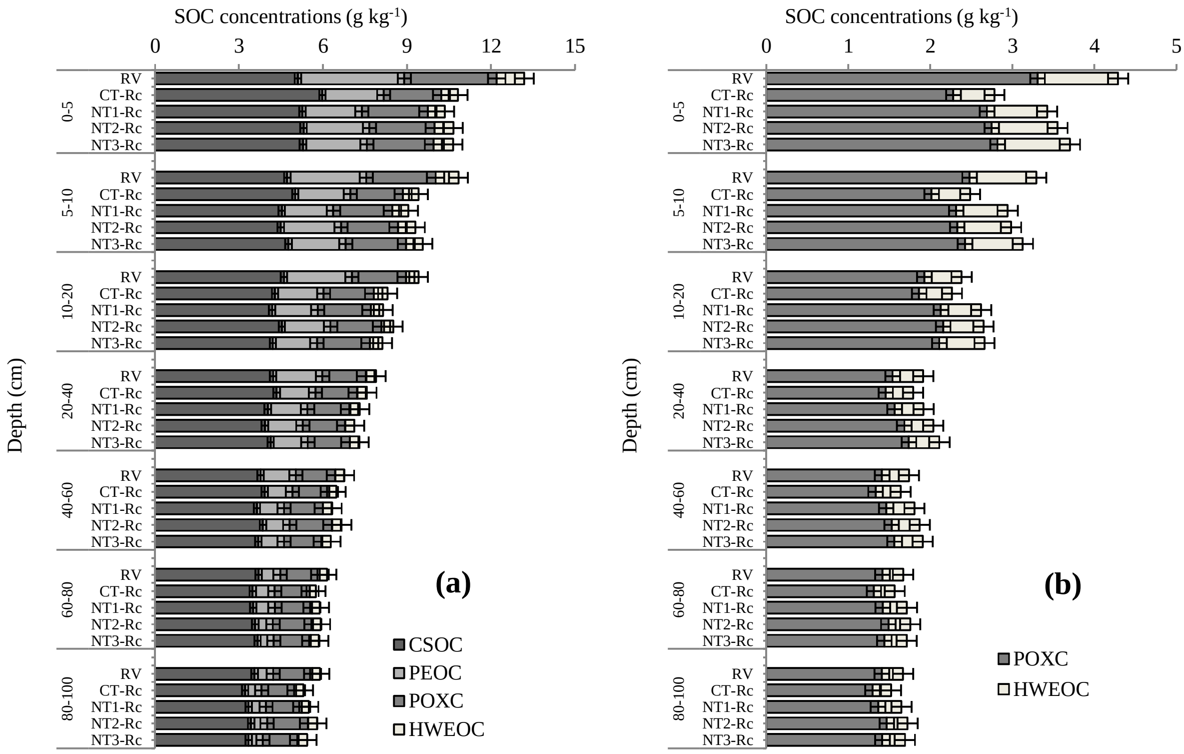


Figure 4.1. Concentrations of (a) hot water-extractable organic C (HWEOC) and permanganate oxidizable C (POXC), pyrophosphate extractable organic C and chemically stabilized organic C (CSOC) in 2011, and (b) HWEOC and POXC in 2013 in 0- to 100-cm depth under rice- based cropping systems. Error bars represent the standard error of the mean.

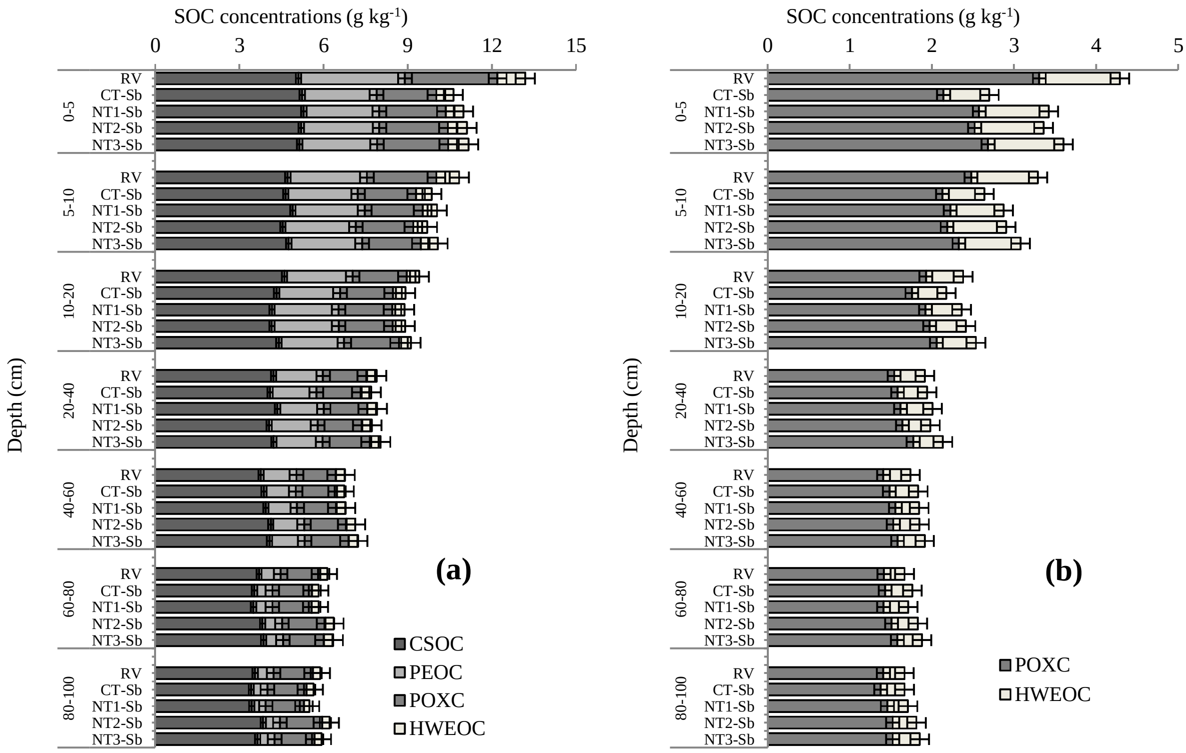


Figure 4.2. Concentrations of (a) hot water-extractable organic C (HWEOC) and permanganate oxidizable C (POXC), pyrophosphate extractable organic C and chemically stabilized organic C (CSOC) in 2011, and (b) HWEOC and POXC in (b) 2013 in 0- to 100-cm depth under soybean-based cropping systems. Error bars represent the standard error of the mean.

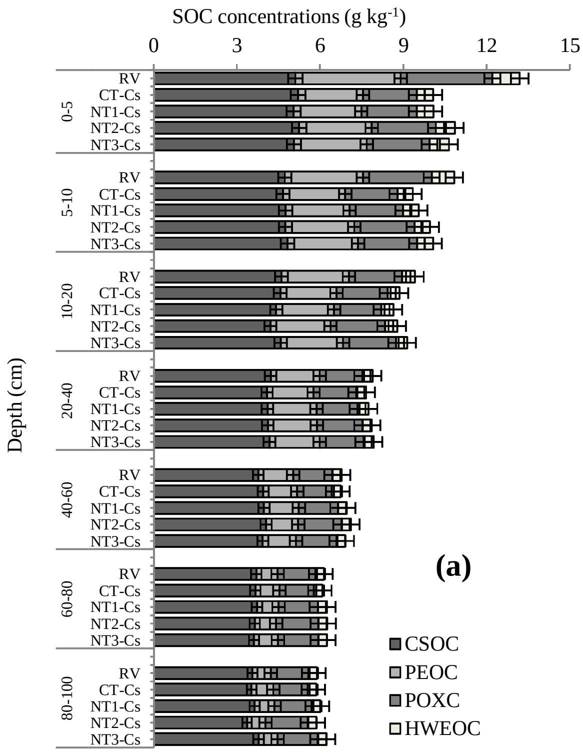


Figure 4.3. Concentrations of (a) hot water-extractable organic C (HWEOC) and permanganate oxidizable C (POXC), pyrophosphate extractable organic C and chemically stabilized organic C (CSOC) in 2011, and (b) HWEOC and POXC in 2013 in 0- to 100-cm depth under cassava-based cropping systems. Error bars represent the standard error of the mean.

Table 4.1

Land use, crop sequence, and carbon input in the five-year experiment period (2009-2013)

Land use	Crop sequence	C input (Mg ha^{-1}) Cumulative	Annual
Rice-based cropping systems			
CT-Rc	Mb/Rc – Mb/Rc – Mb/Rc – Mb/Rc – Mb/Rc	14.22	2.84
NT1-Rc	Mt/Rc+St – Mt+Cr/Rc+St – St(2010)/Rc+St – St(2011)[¥]/Rc+St – Mt+St(2012)/Rc+St	31.75	6.35
NT2-Rc	Mt/Rc+St – Mt+Cr+St (2009)/Mz+St – Mt+Cr+St (2010)/Rc+St – St(2011)/Mz+St – St (2012)/Rc+St	30.29	6.06
NT3-Rc	Mt/Mz+St – Mt+Cr+St (2009)/Rc+St – St (2010)/Mz+St – St (2011)/Rc+St – St (2012)/Mz+St	33.64	6.73
Soybean-based cropping systems			
CT-Sb	Se/Sb – Se/Sb – Se/Sb – Se/Sb – Se/Sb	10.96	2.19
NT1-Sb	Mt/Sb+Brz – Brz(2009)/Sb+St – Mt/Sb+St+Sg – Mt/Sb+St – Sr+St (2012)/Sb+St+Sg	36.62	7.32
NT2-Sb	Mt+/Sb+St – Mt+Cr+St (2009)/Mz+St – Mt/Sb+St – Mt+Cr/Mz+St – Sr+St (2012)/Sb+St	35.47	7.09
NT3-Sb	Mt/Mz+Brz – Mt/Sb+St – Mt+Cr/Mz+St – St (2011)/Sb+St – Sg+Cr+St (2012)/Mz+St	39.25	7.85
Cassava-based cropping systems			
CT-Cs	Cs – Cs – Cs – Cs – Cs	8.06	1.61
NT1-Cs	Cs+St – Cs+St – Cs+St – Cs+St – Cs+St	19.54	3.91
NT2-Cs	Cs+St – Mt+St (2009)/Mz+St – St (2010)/Cs+St – Mt+Cr+St (2011)/Mz+St – St (2012)/Cs+St	21.70	4.34
NT3-Cs	Mt/Mz+St – Cs+St – Mt+Cr+St (2010)/Mz+St – Cs+St – Mt+Cr+St (2012)/Mz3ed c+St	25.27	5.05

Mb: mung bean (*Vigna radiata*); Rc: rice (*Oryza sativa* L.); Mt: millet (*Pennisetum typhoides* Burm); St: *Stylosanthes guianensis*; Cr: *Crotalaria juncea*; Mz: maize (*Zea mays* L.); Se: sesame (*Sesamum indicum*); Sb: soybean (*Glycine max* (L.) Merr.); Brz: *Brachiaria ruziziensis* cv. ruzi; Cs: cassava (*Manihot esculenta*); Sg: sorghum (*Sorghum bicolor* L.) [¥] St (*Stylosanthes guianensis)* left from the year in brackets. "/" indicates relay cropping with varying planting dates; "+" indicates crops planted in association (same or staggered sowing dates).

Table 4.2

Hot water-extractable organic C (HWEOC) stocks in 0- to 100-cm depth under rice-based cropping systems at two sampling time (2011 and 2013)

		HWEOC (Mg C ha^{-1})				
Year	Depth (cm)	RV[a]	CT-Rc[b]	NT1-Rc	NT2-Rc	NT3-Rc
2011	0–5	0.49 A	0.29 Bb	0.30 Bab	0.34 Bab	0.35 Ba
	5–10	0.43 A	0.29 Bns	0.30 B	0.32 B	0.31 B
	10–20	0.50 ns	0.54	0.49	0.46	0.50
	20–40	0.85 ns	0.81	0.85	0.74	0.79
	40–60	0.73 ns	0.57	0.74	0.77	0.69
	60–80	0.53 ns	0.45	0.57	0.60	0.59
	80–100	0.55 AB	0.54 Bns	0.55 AB	0.66 A	0.63 AB
	0-100	4.08 A	3.49 Bns	3.80 AB	3.89 AB	3.86 AB
2013	0–5	0.49 A	0.25 Cb	0.37 Ba	0.40 ABa	0.44 ABa
	5–10	0.43 ns	0.25	0.33	0.34	0.37
	10–20	0.50 ns	0.44	0.54	0.54	0.61
	20–40	0.85 ns	0.76	0.81	0.80	0.85
	40–60	0.73 ns	0.68	0.76	0.77	0.77
	60–80	0.53 ns	0.53	0.63	0.56	0.57
	80–100	0.55 ns	0.47	0.62	0.55	0.58
	0-100	4.08 ns	3.38	4.06	3.96	4.19

RV: reference vegetation; CT: conventional tillage; NT: no-till; [a] Comparison between tillage systems CT-Rc, NT1-Rc, NT2-Rc, NT3-Rc and reference vegetation (RV). Uppercase letters within the same row indicate difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison between tillage systems CT-Rc, NT1-Rc, NT2-Rc and NT3-Rc. Lowercase letters within the same row indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 4.3

Permanganate oxidizable C (POXC) stocks in 0- to 100-cm depth under rice-based cropping systems at two sampling time (2011 and 2013)

		POXC (Mg C ha^{-1})				
Year	Depth (cm)	RV[a]	CT-Rc[b]	NT1-Rc	NT2-Rc	NT3-Rc
2011	0–5	1.65 A	1.03 Cb	1.18 Ba	1.16 Ba	1.19 Ba
	5–10	1.30 A	0.99 Cns	1.11 BC	1.07 BC	1.13 B
	10–20	2.12 ns	1.98	2.09	2.01	2.09
	20–40	3.52 ns	3.40	3.41	3.47	3.41
	40–60	3.15 AB	2.95 Bb	3.12 ABb	3.37 Aa	3.04 Bb
	60–80	2.97 AB	2.65 Cb	2.78 BCab	3.00 Aa	2.78 BCb
	80–100	2.99 ns	2.60 b	2.70 ab	3.12 a	2.69 ab
	0-100	17.70 ns	15.60	16.39	17.20	16.33
2013	0–5	1.65 A	1.14 Cb	1.34 Ba	1.37 Ba	1.41 Ba
	5–10	1.30 A	1.06 Bns	1.22 A	1.22 A	1.27 A
	10–20	2.12 ns	2.05	2.35	2.38	2.33
	20–40	3.52 ns	3.32	3.58	3.84	3.97
	40–60	3.15 ns	2.99	3.27	3.42	3.49
	60–80	2.97 ns	2.74	2.99	3.12	3.02
	80–100	2.99 ns	2.72	2.89	3.11	3.02
	0-100	17.70 ns	16.02	17.64	18.46	18.51

RV: reference vegetation; CT: conventional tillage; NT: no-till; [a] Comparison between tillage systems CT-Rc, NT1-Rc, NT2-Rc, NT3-Rc and reference vegetation (RV). Uppercase letters within the same row indicate difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison between tillage systems CT-Rc, NT1-Rc, NT2-Rc and NT3-Rc. Lowercase letters within the same row indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 4.4

Stocks of pyrophosphate extractable organic C (PEOC) and chemically stabilized organic C (CSOC) in 0- to 100-cm depth under rice-based cropping systems in 2011

	SOC pools				
Depth (cm)	RV[a]	CT-Rc[b]	NT1-Rc	NT2-Rc	NT3-Rc
PEOC (Mg C ha^{-1})					
0–5	1.89 A	1.10 Bns	1.06 B	1.17 B	1.14 B
5–10	1.48 A	1.03 Bns	0.97 B	1.13 B	1.07 B
10–20	2.68 A	1.91 Bns	1.80 B	1.92 B	1.74 B
20–40	4.04 A	3.16 Bns	3.25 B	3.10 B	3.03 B
40–60	2.83 ns	2.21	2.17	2.14	2.06
60–80	1.63 ns	1.64	1.62	1.33	1.22
80–100	1.41 ns	1.26	1.30	1.21	1.07
0-100	15.96 A	12.31 Bns	12.17 B	12.00 B	11.33 B
CSOC (Mg C ha^{-1})					
0–5	2.55 ns	2.98	2.63	2.66	2.64
5–10	2.48 ns	2.63	2.38	2.36	2.51
10–20	5.09 ns	4.73	4.61	5.02	4.64
20–40	9.64 ns	9.88	9.21	8.96	9.44
40–60	8.43 ns	8.76	8.16	8.60	8.28
60–80	7.75ns	7.35	7.37	7.55	7.65
80–100	7.56 ns	6.83	7.13	7.28	7.08
0-100	43.50 ns	43.16	41.49	42.43	42.24

RV: reference vegetation; CT: conventional tillage; NT: no-till; [a] Comparison between tillage systems CT-Rc, NT1-Rc, NT2-Rc, NT3-Rc and reference vegetation (RV). Uppercase letters within the same row indicate difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison between tillage systems CT-Rc, NT1-Rc, NT2-Rc and NT3-Rc. Lowercase letters within the same row indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 4.5

Hot water-extractable organic C (HWEOC) stocks in 0- to 100-cm depth under soybean-based cropping systems at two sampling time (2011 and 2013)

		HWEOC (Mg C ha^{-1})				
Year	Depth (cm)	RV[a]	CT-Sb[b]	NT1-Sb	NT2-Sb	NT3-Sb
2011	0–5	0.49 A	0.30 Bns	0.31 B	0.34 B	0.36 B
	5–10	0.43 A	0.29 BCab	0.27 BCb	0.26 Cb	0.32 Ba
	10–20	0.50 ns	0.49	0.47	0.49	0.47
	20–40	0.85 ns	0.87	0.81	0.83	0.87
	40–60	0.73 ns	0.58	0.71	0.71	0.74
	60–80	0.53 ns	0.49	0.51	0.65	0.71
	80–100	0.55 ns	0.53	0.42	0.54	0.54
	0-100	4.08 ns	3.55	3.50	3.82	4.01
2013	0–5	0.49 A	0.28 Bb	0.42 Aa	0.42 Aa	0.46 Aa
	5–10	0.43 ns	0.27	0.34	0.38	0.39
	10–20	0.50 ns	0.41	0.49	0.49	0.53
	20–40	0.85 ns	0.83	0.89	0.78	0.82
	40–60	0.73 ns	0.78	0.65	0.71	0.74
	60–80	0.53 ns	0.70	0.63	0.68	0.63
	80–100	0.55 ns	0.64	0.54	0.62	0.70
	0-100	4.08 ns	3.91	3.96	4.08	4.27

RV: reference vegetation; CT: conventional tillage; NT: no-till; [a] Comparison between tillage systems CT-Sb, NT1-Sb, NT2-Sb, NT3-Sb and reference vegetation (RV). Uppercase letters within the same row indicate difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison between tillage systems CT-Sb, NT1-Sb, NT2-Sb and NT3-Sb. Lowercase letters within the same row indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 4.6

Permanganate oxidizable C (POXC) stocks in 0- to 100-cm depth under soybean-based cropping systems at two sampling time (2011 and 2013)

		POXC (Mg C ha^{-1})				
Year	Depth (cm)	RV[a]	CT-Sb[b]	NT1-Sb	NT2-Sb	NT3-Sb
2011	0–5	1.65 A	1.07 Cns	1.18 BC	1.22 BC	1.27 B
	5–10	1.30 A	1.09 Bns	1.09 B	1.08 B	1.10 B
	10–20	2.12 ns	2.09	2.12	2.13	2.15
	20–40	3.52 ns	3.59	3.55	3.59	3.87
	40–60	3.15 ns	3.29	3.15	3.37	3.52
	60–80	2.97 B	2.97 Bb	2.95 Bb	3.24 Aa	3.06 ABab
	80–100	2.99 ns	2.93	2.91	3.23	3.04
	0-100	17.70 ns	17.03	16.95	17.86	18.01
2013	0–5	1.65 A	1.07 Cb	1.29 Ba	1.26 Ba	1.34 Ba
	5–10	1.30 ns	1.12	1.17	1.15	1.22
	10–20	2.12 ns	1.94 b	2.12 ab	2.17 a	2.27 a
	20–40	3.52 ns	3.62	3.70	3.75	4.04
	40–60	3.15 ns	3.31	3.48	3.41	3.54
	60–80	2.97 ns	3.00	2.96	3.19	3.33
	80–100	2.99 ns	2.91	3.10	3.23	3.25
	0-100	17.70 AB	16.95 Bb	17.82 ABab	18.14 ABab	18.99 Aa

RV: reference vegetation; CT: conventional tillage; NT: no-till; [a] Comparison between tillage systems CT-Sb, NT1-Sb, NT2-Sb, NT3-Sb and reference vegetation (RV). Uppercase letters within the same row indicate difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison between tillage systems CT-Sb, NT1-Sb, NT2-Sb and NT3-Sb. Lowercase letters within the same row indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 4.7

Stocks of pyrophosphate extractable organic C (PEOC) and chemically stabilized organic C (CSOC) in 0- to 100-cm depth under soybean-based cropping systems in 2011

	SOC pools				
Depth (cm)	RV[a]	CT-Sb[b]	NT1-Sb	NT2-Sb	NT3-Sb
PEOC (Mg C ha^{-1})					
0–5	1.89 A	1.33 Bns	1.35 B	1.39 B	1.38 B
5–10	1.48 ns	1.35	1.35	1.37	1.37
10–20	2.68 ns	2.50	2.61	2.63	2.57
20–40	4.04 ns	3.77	3.76	3.95	3.98
40–60	2.83 ns	2.54	2.49	2.65	2.80
60–80	1.63 ns	1.34	1.42	1.45	1.44
80–100	1.41 ns	1.21	1.07	1.25	1.29
0-100	15.96 ns	14.04	14.05	14.69	14.83
CSOC (Mg C ha^{-1})					
0–5	2.55 ns	2.61	2.64	2.60	2.57
5–10	2.48 ns	2.44	2.58	2.39	2.50
10–20	5.09 ns	4.78	4.59	4.58	4.85
20–40	9.64 ns	9.34	9.97	9.27	9.66
40–60	8.43 ns	8.66	8.81	9.21	9.11
60–80	7.75 ns	7.42	7.41	8.02	8.09
80–100	7.56 ns	7.30	7.29	8.24	7.75
0-100	43.50 ns	42.55	43.29	44.31	44.53

RV: reference vegetation; CT: conventional tillage; NT: no-till; [a] Comparison between tillage systems CT-Sb, NT1-Sb, NT2-Sb, NT3-Sb and reference vegetation (RV). Uppercase letters within the same row indicate difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison between tillage systems CT-Sb, NT1-Sb, NT2-Sb and NT3-Sb. Lowercase letters within the same row indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 4.8

Hot water-extractable organic C (HWEOC) stocks in 0- to 100-cm depth under cassava-based cropping systems at two sampling time (2011 and 2013)

		HWEOC (Mg C ha^{-1})				
Year	Depth (cm)	RV[a]	CT-Cs[b]	NT1-Cs	NT2-Cs	NT3-Cs
2011	0–5	0.49 A	0.29 Cb	0.30 Cb	0.34 Ba	0.35 Ba
	5–10	0.43 A	0.29 Bns	0.29 B	0.29 B	0.30 B
	10–20	0.50 ns	0.47	0.48	0.47	0.44
	20–40	0.85 ns	0.80	0.90	0.76	0.81
	40–60	0.73 ns	0.54	0.70	0.76	0.62
	60–80	0.53 ns	0.49	0.66	0.63	0.62
	80–100	0.55 ns	0.51	0.51	0.58	0.63
	0-100	4.08 ns	3.39	3.84	3.83	3.77
2013	0–5	0.49 A	0.26 Cb	0.37 Ba	0.40 ABa	0.42 ABa
	5–10	0.43 ns	0.26	0.29	0.34	0.36
	10–20	0.50 ns	0.48	0.55	0.56	0.53
	20–40	0.85 ns	0.74	0.82	0.89	0.82
	40–60	0.73 ns	0.66	0.71	0.73	0.75
	60–80	0.53 ns	0.53	0.64	0.61	0.63
	80–100	0.55 ns	0.48	0.61	0.54	0.59
	0-100	4.08 ns	3.41	3.99	4.07	4.10

RV: reference vegetation; CT: conventional tillage; NT: no-till; [a] Comparison between tillage systems CT-Cs, NT1-Cs, NT2-Cs, NT3-Cs and reference vegetation (RV). Uppercase letters within the same row indicate difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison between tillage systems CT-Cs, NT1-Cs, NT2-Cs and NT3-Cs. Lowercase letters within the same row indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 4.9

Permanganate oxidizable C (POXC) stocks in 0- to 100-cm depth under cassava-based cropping systems at two sampling time (2011 and 2013)

		POXC (Mg C ha^{-1})				
Year	Depth (cm)	RV[a]	CT[b]	NT1	NT2	NT3
2011	0–5	1.65 A	0.97 Cb	1.00 Cb	1.16 Ba	1.13 Ba
	5–10	1.30 ns	0.99	1.01	1.14	1.12
	10–20	2.12 ns	2.03	1.89	2.18	2.10
	20–40	3.52 ns	3.52	3.36	3.73	3.62
	40–60	3.15 B	2.95 Cc	3.18 Bb	3.49 Aa	3.34 Aa
	60–80	2.97 BC	2.77 Cc	2.97 BCbc	3.22 Aa	3.09 ABab
	80–100	2.99 BC	2.78 Cc	2.98 BCbc	3.28 Aa	3.09 ABab
	0-100	17.70 AB	16.01 Cns	16.39 BC	18.20 A	17.49 AB
2013	0–5	1.65 A	0.93 Cb	1.05 Cb	1.29 Ba	1.33 Ba
	5–10	1.30 ns	1.02	1.03	1.19	1.16
	10–20	2.12 ns	1.89	1.95	2.20	2.22
	20–40	3.52 ns	3.49	3.44	3.74	3.80
	40–60	3.15 ns	3.10	3.09	3.16	3.32
	60–80	2.97 ns	2.88	3.02	3.10	3.09
	80–100	2.99 ns	2.80	2.91	2.98	2.94
	0-100	17.70 ns	16.11	16.49	17.66	17.86

RV: reference vegetation; CT: conventional tillage; NT: no-till; [a] Comparison between tillage systems CT-Cs, NT1-Cs, NT2-Cs, NT3-Cs and reference vegetation (RV). Uppercase letters within the same row indicate difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison between tillage systems CT-Cs, NT1-Cs, NT2-Cs and NT3-Cs. Lowercase letters within the same row indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 4.10

Stocks of pyrophosphate extractable organic C (PEOC) and chemically stabilized organic C (CSOC) in 0- to 100-cm depth under cassava-based cropping systems in 2011

	SOC pools				
Depth (cm)	RV[a]	CT[b]	NT1	NT2	NT3
PEOC (Mg C ha^{-1})					
0–5	1.89 A	1.17 Bb	1.22 Bb	1.31 Ba	1.31 Ba
5–10	1.48 A	1.18 C ns	1.21 BC	1.30 BC	1.33 AB
10–20	2.68 ns	2.24	2.29	2.39	2.48
20–40	4.04 ns	3.83	4.04	4.03	4.13
40–60	2.83 ns	2.75	2.81	2.59	2.67
60–80	1.63 ns	1.82	1.61	1.60	1.80
80–100	1.41 ns	1.67	1.53	1.39	1.47
0-100	15.96 ns	14.66	14.71	14.61	15.18
CSOC (Mg C ha^{-1})					
0–5	2.55 ns	2.60	2.52	2.62	2.52
5–10	2.48 ns	2.45	2.50	2.49	2.53
10–20	5.09 ns	5.04	4.87	4.64	5.05
20–40	9.64 ns	9.33	9.36	9.39	9.54
40–60	8.43 ns	8.84	8.89	9.06	8.79
60–80	7.75 ns	7.69	7.81	7.66	7.58
80–100	7.56 ns	7.53	7.71	7.15	8.05
0-100	43.50 ns	43.48	43.66	43.01	44.06

RV: reference vegetation; CT: conventional tillage; NT: no-till; [a] Comparison between tillage systems CT-Cs, NT1-Cs, NT2-Cs, NT3-Cs and reference vegetation (RV). Uppercase letters within the same row indicate difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison between tillage systems CT-Cs, NT1-Cs, NT2-Cs and NT3-Cs. Lowercase letters within the same row indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 4.11

β-glucosidase and arylsulfatase activities at 0- to 20-cm depth under rice-based cropping systems in 2011

	Enzymatic activities				
Depth (cm)	RV[a]	CT-Rc[b]	NT1-Rc	NT2-Rc	NT3-Rc
β-glucosidase (mg PNP kg^{-1} soil h^{-1})					
0–5	80.1 A	31.0 Cb	35.7 BCa	36.6 Ba	37.2 Ba
5–10	50.3 A	27.9 Bns	29.4 B	29.1 B	29.2 B
10–20	25.1 ns	19.0	19.8	18.8	20.0
Arylsulfatase (mg PNP kg^{-1} soil h^{-1})					
0–5	26.6 A	15.8 Bns	16.1 B	16.7 B	16.8 B
5–10	19.7 A	12.3 Bns	12.0 B	12.4 B	13.4 B
10–20	9.9 ns	7.7	7.5	7.7	8.1

RV: reference vegetation; CT: conventional tillage; NT: no-till; [a] Comparison between tillage systems CT-Rc, NT1-Rc, NT2-Rc, NT3-Rc and reference vegetation (RV). Uppercase letters within the same row indicate difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison between tillage systems CT-Rc, NT1-Rc, NT2-Rc and NT3-Rc. Lowercase letters within the same row indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 4.12

β-glucosidase and arylsulfatase activities at 0- to 20-cm depth under soybean-based cropping systems in 2011

	Enzymatic activities				
Depth (cm)	RV[a]	CT-Sb[b]	NT1-Sb	NT2-Sb	NT3-Sb
β-glucosidase (mg PNP kg^{-1} soil h^{-1})					
0–5	80.1 A	29.2 Cb	35.6 BCab	38.3 Ba	38.2 Ba
5–10	50.3 A	28.7 Bns	28.9 B	28.1 B	29.7 B
10–20	25.1 A	21.2 ABns	21.7 AB	20.6 B	21.2 AB
Arylsulfatase (mg PNP kg^{-1} soil h^{-1})					
0–5	26.6 A	13.2 Cb	15.3 BCab	19.4 Ba	19.1 Ba
5–10	19.7 A	12.7 B	13.3 B	13.6 B	13.7 B
10–20	9.9 ns	8.1	8.1	8.3	8.3

RV: reference vegetation; CT: conventional tillage; NT: no-till; [a] Comparison between tillage systems CT-Sb, NT1-Sb, NT2-Sb, NT3-Sb and reference vegetation (RV). Uppercase letters within the same row indicate difference among RV and tillage treatments at P ≤ 0.05 by LSD. [b] Comparison between tillage systems CT-Sb, NT1-Sb, NT2-Sb and NT3-Sb. Lowercase letters within the same row indicate difference between tillage treatments at P ≤ 0.05 by LSD. ns: not significant.

Table 4.13

β-glucosidase and arylsulfatase activities at 0- to 20-cm depth under cassava-based cropping systems in 2011

	Enzymatic activities				
Depth (cm)	RV[a]	CT-Cs[b]	NT1-Cs	NT2-Cs	NT3-Cs
β-glucosidase (mg PNP kg^{-1} soil h^{-1})					
0–5	80.1 A	23.5 Cb	30.9 BCab	36.2 Ba	37.6 Ba
5–10	50.3 A	24.4 Cns	26.4 BC	31.1 BC	32.9 B
10–20	25.1 ns	20.8	19.5	21.8	22.4
Arylsulfatase (mg PNP kg^{-1} soil h^{-1})					
0–5	26.6 A	11.2 Db	13.5 CDb	16.5 BCa	16.7 Ba
5–10	19.7 A	12.2 Bns	13.0 B	13.5 B	14.0 B
10–20	9.9 ns	7.3	7.3	7.8	8.7

RV: reference vegetation; CT: conventional tillage; NT: no-till; [a] Comparison between tillage systems CT-Cs, NT1-Cs, NT2-Cs, NT3-Cs and reference vegetation (RV). Uppercase letters within the same row indicate difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison between tillage systems CT-Cs, NT1-Cs, NT2-Cs and NT3-Cs. Lowercase letters within the same row indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

CHAPTER 5

Dynamics of Soil Aggregate-associated Organic Carbon under Short-term Conservation Agriculture Cropping Systems

Abstract

Conservation agriculture has a potential to enhance soil aggregation and consequently to sequester soil organic C (SOC). Changes in the proportions of water stable soil aggregates and aggregate-associated SOC, total N and permanganate oxidizable C (POXC) due to soil management (i.e., conventional tillage – CT, no-till – NT) and crop rotations in rice-, soybean- and cassava-based cropping systems (RcCS, SbCS and CsCS, respectively) were studied in a clayed soil. There were four treatments in each cropping system comprising of one CT and three NT treatments arraying in randomized complete block design with three replicates. Soil aggregate samples were collected in 0-5, 5-10 and 10-20 cm depths after three years of the experiments. On average, the proportions of large macroaggregates (8-19 mm) in the 0-5 cm depth under NT increased 23%, 39% and 53% in RcCS, SbCS, and CsCS, respectively, and consequently mean weight diameter (MWD), mean geometric diameter (MGD) and aggregate stability index (ASI) compared with those under CT. The tillage and crop rotations did not significantly affect the majority of SOC and total N associated with aggregate size classes in all depths in RcCS and CsCS but a recovery trend was noticed under NT in 0-5 cm depth. Although SOC did not differ, aggregate-associated POXC under NT significantly increased in most size classes in 0-5 cm depth in the three cropping systems. On average, and across all aggregate size classes, NT accumulated SOC concentrations over CT by 11%, 7% and 6%, total N concentrations by 3%, 11% and 15% and POXC concentrations by 18%, 20% and 15% for RcCS, SbCS, and CsCS, respectively. The increasing trend was also observed in the subsoil

layers. As a consequence of increased POXC, C management index (CMI) under NT was promoted indicating the greater lability of SOC. The results of CP-MAS ^{13}C NRM measurement of the large macroaggregate in 0-5 cm showed that humic acid from soils under NT tended to have higher proportions of aliphatic C than under CT while in reverse for aromatic C. In addition, there were positive correlations between large macroaggregate-associated SOC and soil aggregation indices (i.e., MWD, MGD, ASI) in 0-5 cm depth in the three cropping systems. In conclusion, CT decreased the proportion of large macroaggregates, soil aggregation indices and aggregate-associated SOC, total N and POXC while the adoption of NT showed a potential to restore them back to the antecedent levels found under reference vegetation (RV).

5.1 Introduction

Soils can be either a sink for or a source of CO_2 depending on land use and management (Lal, 2003b, 2010). Changes in agricultural management practices to intensify crop production profoundly affect soil organic C (SOC) dynamics (Chivenge et al., 2007; Lal, 1997; Six et al., 2002). Soil organic matter (SOM) stabilization is controlled by three main mechanisms including (a) chemically innate recalcitrance, (b) protection through interaction with minerals, and (c) occlusion in aggregates (Mikutta et al., 2006). SOC and soil aggregation are the principal determinants of soil productivity and sustainability and closely link one to another (Feller & Beare, 1997). An increase in SOC enhances soil aggregation because it is considered one of the major aggregating agents (Tisdall & Oades, 1982).

Soil aggregate stability plays a potential role in the ability of soil to sequester SOC and might be used as a judicious strategy to mitigate the increase in atmospheric CO_2 concentration. Soil aggregation has a major influence on root development, C cycling and soil resistance to erosion (Kay, 1998). The formation of stable soil aggregates is related to mineralogy, texture and the quality and quantity of organic matter inputs (Feller & Beare, 1997). The proportions of soil water stable aggregates often change rapidly when tillage practices and crop rotations are modified (Angers et al., 1992). Aggregate-associated SOC provides strength and stability and counters the impact of destructive forces and it is an important reservoir of soil C because of its physical protection from microbial and enzymatic degradation (Bajracharya et al., 1997). A positive relationship between SOC and aggregate stability was also reported (Dutartre et al., 1993; Tisdall & Oades, 1982). Thus, maintaining high soil aggregate stability might lead to increased SOC sequestration, an indicator of sustainable soil management practices. It has also been known that iron and aluminum oxides and 1:1 clay minerals are the dominant binding agents in oxide-rich soils in the tropics (Oades & Waters, 1991; Six et al., 2002). Amézketa (1999) reviewed that the inorganic stabilizing agents (i.e., clays, polyvalent metal cations, oxides, hydroxides of iron and aluminum, calcium and magnesium carbonates, gypsum) affect soil aggregate formation and stabilization. They might offer protection to SOC against strong structural alterations.

The practices of conventional tillage (CT) reduce the proportions of macroaggregates by breaking down of soil aggregates (Zotarelli et al., 2007), thus hastening SOC oxidation through stimulation of soil microbial biomass and activity (D. Guo et al., 2013; Six et al., 2004) and affecting soil drying and wetting (Six et al., 2004). Unlike CT, no-till (NT) has less deleterious effects on soil structure and maintains or sequesters SOC (Lal & Kimble, 1997). Enhanced soil aggregation through NT can enhance the physical protection of SOC against losses due either to mineralization or detachability and erosion (Feller & Beare, 1997). It is observed that soils under NT have significantly higher aggregate stability, more macroaggregates-occluded microaggregates and a greater SOC protection than under CT (Barreto et al., 2009; Denef et al., 2004). Soil aggregate stability is a function of the liberation of aggregating agents, principally by microorganisms, through the decomposition of organic residues (Cosentino et al., 2006). The constant inputs of organic materials under NT generate a range of aggregating agents such as fungal hyphae, microbial bio-products (Haynes & Francis, 1993) and root exudates (Guggenberger et al., 1999). The role of plant derived polysaccharides in aggregate stability may be also found in the fact that they may originate from plant detritus or from plant exudates (Feller & Beare, 1997). The quantification of labile SOC fraction like permanganate oxidizable C (POXC) might be crucial to indicate the presence of aggregating agents because of its positive correlation to soil microbial activity including soil microbial biomass C (SMBC), soluble carbohydrate C and total C (Weil et al., 2003).

Dynamics of large macro-aggregates (8-19 mm) may be a good indicator of potential C in response to land use change and management due to their importance to protect recently deposited labile SOC (Castro Filho et al., 2002). Tivet, Sá, Lal, Briedis, et al. (2013) emphasized that continuous practices of CT negatively impacted distribution of water-stable aggregates and loss of large macro-aggregates (8-19 mm) in a tropical red Latosol. The ability of NT practices in rotation or association with cover crops to increase SOC sequestration varies among systems, locations and soil depths. To manage individual soils effectively, the understanding of the mechanisms that control SOC dynamics should be improved. Forest clearance to expand agricultural land for the development of annual upland crops (i.e., rice, maize, cassava, soybean, and mungbean) to satisfy the needs of growing population in Cambodia has exacerbated growing concern over land degradation (Belfield et al., 2013; Hean, 2004; Poffenberger, 2009; UNDP, 2010) due to the CT practices that disrupt soil macroaggregates causing an increased release of CO_2 to the atmosphere. Considering the exponential increase of degraded soil cultivated with CT, the application of NT has been introduced. However, the role of NT and residue retention in aggregate formation is poorly documented in tropical agro-ecosystems in general and in Cambodia in particular. The challenges to develop agricultural management practices to sequester SOC through enhancement of soil aggregation and aggregate stability are necessary to define sustainable crop production intensification in this country. The quantification of aggregate-associated SOC and POXC distribution among aggregate size classes is fundamental to a better understanding of the short-term effect of conservation agriculture (CA) on SOC sequestration and the mechanism by which soils can sequester SOC. This will enable realistic evaluation of the potential of crop rotation schemes for SOC sequestration. Therefore, this study was conducted to quantify the changes in aggregate size distribution and levels of aggregate-associated total SOC, total N and POXC after three-year CT and NT management practices in a clayed soil in a tropical savanna agro-ecosystem.

5.2 Materials and Methods

Detailed descriptions of the site, experiments and biomass-C inputs are reported in Chapter 3. Briefly, this study was executed in existing field experiments initiated in 2009 at Bosknor Research Station, Kampong Cham, Cambodia (Latitude 12°12′30″N, longitude 105°19′7″E and 118 m elevation). Three distinct experiments comprised of (a) rice- (b) soybean- and (c) cassava-based cropping systems (RcCS, SbCS, and CsCS, restectively). The plots were arrayed in randomized complete block design with three replicates and four treatments consisting of (a) CT in which main crops were planted in annual succession for rice and soybean (i.e., mungbean/rice–CT-Rc, sesame/soybean–CT-Sb) and mono-cropping for cassava (CT-Cs); (b) NT in which main crops were planted in a one year frequency pattern (NT1-Rc, NT1-Sb, NT1-Cs); and (c) and (d) NT in which main crops were planted in bi-annual rotations with maize, the two plots in these bi-annual rotations being NT2-Rc, NT3-Rc for rice, NT2-Sb, NT3-Sb for soybean and NT2-Cs, NT3-Cs for cassava. The basal P fertilizer was applied by surface banding with thermo phosphate (i.e., 16% P_2O_5, 31% CaO and 16% MgO), and fractioned top dressing on main crops for N and K, using urea (46 % N) and potassium chloride (60 % K_2O), respectively. The total fertilizer input (2009-2011) was 161 kg ha^{-1} N, 144 kg ha^{-1} P_2O_5, 120 kg ha^{-1} K_2O_5 for rice, 69 kg ha^{-1} N, 144 kg ha^{-1} P_2O_5, 180 kg ha^{-1} K_2O_5 for soybean, 230 kg ha^{-1} N, 144 kg ha^{-1} P_2O_5, 210 kg ha^{-1} K_2O_5 for cassava, and 230 kg ha^{-1} N, 144 kg ha^{-1} P_2O_5, 120 kg ha^{-1} K_2O_5 for maize. The aboveground biomass of main and cover crops were measured and the belowground biomass-C inputs were estimated on the basis of the root to shoot ratio (RS ratio) index. The details of cumulative and annual biomass-C inputs (2009-2011) in each cropping system are presented in Table 5.1.

5.2.1 Water stable aggregate. Soil aggregate samples were taken in 70 cm × 70 cm pits dug to 30 cm in November 2011 after three years of the experiment. Two clods for water-stable aggregates were collected from each depth (0-5, 5-10 and 10-20 cm) in each plot in the three cropping systems and reference vegetation (RV). Soon after sampling, each sample was wrapped in plastic film to prevent moisture loss and excessive drying and to ease breakdown during transportation from Cambodia to Brazil. Following capillary rewetting of each sample to field moisture capacity, colds were softly broken along their natural cleavage planes before passing through 19-mm mesh sieve (Castro Filho et al., 2002). The use of 19-mm sieve homogenizes samples and does not underestimate the production of large macroaggregate under NT (Castro Filho et al., 2002; Madari et al., 2005). Aggregate size classes were obtained by the wet sieving procedure (Kemper & Rosenau, 1986) using a nest of seven sieves (8, 4, 2, 1, 0.5, 0.25 and 0.053 mm). The sieving procedure was simultaneously performed trice for each sample due to variability in the distribution of soil aggregates. Prior to immersing in water, 60 g samples were evenly spread on wetted filter paper on top of the 8-mm sieve and rewetted by capillary rise of water for 10 min, and wet sieved at 30 oscillations min^{-1} for 15 min. At the end of vertical oscillation, stable aggregates retrieved at each sieve were carefully backwashed into pre-weighed containers, oven-dried at 40 ºC until a constant weight, and weighed. The following classification was used herein: macroaggregates (2-4 to 8-19 mm), mesoaggregate (0.25-0.5 to 1-2 mm) and microaggregate (0.053-0.25 mm).

5.2.2 Distribution of water stable aggregates and soil aggregation indices. The proportion of water stable aggregate (WSA) was computed for each size class in relation to the initial dry weight of the sample. Then, three aggregation indices were calculated as follow:

$$\mathrm{MWD} = \int_{i=1}^{n} x_i\, w_i$$

Where, MWD is the mean weight diameter (mm) of aggregates; x_i is the mean diameter of the classes (mm); w_i is the proportion of each aggregate class in relation to the whole.

$$\mathrm{MGD} = \exp\left[\frac{\int_{i=1}^{n} w_i \, log\, x_i}{\int_{i=1}^{n} w_i}\right]$$

Where, MGD is the mean geometric diameter (mm) of aggregates; w_i is the weight of aggregates (g) in a size class with an average diameter x_i.

$$\mathrm{ASI} = \frac{\mathrm{M_r}}{\mathrm{M_t}} \times 100$$

Where, ASI is aggregate stability index; M_r is mass of resistant aggregates; and M_t is the total mass of wet sieved soil.

5.2.3 Concentrations of soil organic C, total N and permanganate oxidizable C associated with aggregate size classes. Sub-samples of each aggregate size class were finely ground (< 150 mm) prior to determination of aggregate-associated SOC and total N by the dry combustion method using an elemental CN analyzer (TruSpec CN, LECO, St. Joseph, USA). Inorganic C in the studied soil was negligible so soil total C (TOC) was considered as SOC.

POXC concentrations in the seven size classes of soil aggregates were performed by the method adapted from Tirol-Padre and Ladha (2004) and Culman et al. (2012). Briefly, 1.5 g of 2 mm-sieved aggregate soils was weighed into 15 mL polypropylene centrifuge tubes. The sample was treated with 10 mL of a stock solution of $KMnO_4$ (60 mM) and shaken on a vortex shaker for 15 sec to suspend the soil in the stock solution. The tubes were horizontally shaken on a table shaker at 200 rpm for 15 min at room temperature, and then centrifuged for 10 min at 4000 rpm. 2 mL of the supernatant was pipetted, transferred to a 125 mL Erlenmeyer flask and diluted with 100 mL deionized water. The absorbance of the solutions was determined at 565 nm using Visible Spectrophotometer (SP-1105), and the amount of the oxidized organic C was calculated from the $KMnO_4$ consumed. The conversion of the absorbance to POXC concentration (g kg^{-1}) was done by using a standard calibration curve, based on the linear relationship between $KMnO_4$ concentrations vs. absorbance at 565 nm. The concentration of POXC was computed as follow:

$$POXC\ (g\ kg^{-1}) = [(mM\ blank - mM\ sample) \times (125/2) \times 10 \times 9] / [1000\ (mL\ L^{-1}) \times wt\ of\ sample\ (g)]$$

where, mM blank and mM sample are the concentrations (mmol L^{-1}) of $KMnO_4$ in the blank and sample, respectively, determined from the standard regression curve; 125/2 = the dilution factor (mL mL^{-1}); 10 = the volume (mL) of $KMnO_4$ added to the soil sample; 9 = the amount of C oxidized from every mole of $KMnO_4$ (g mol^{-1} or mg $mmol^{-1}$).

The C management index (CMI) in each soil aggregate size class was then calculated following the mathematical procedures by Blair, Lefroy, and Lisle (1995) using POXC concentrations. CMI provides a sensitive measure of the rate of change in soil C dynamics of a given system relative to a more stable reference soil. The index was calculated for each of the treatments using a reference sample value obtained from RV.

CMI = CPI × LI × 100

where, CMI is C management index; CPI is carbon pool index; LI is lability index.

The loss of C from a soil with a large C pool is of less consequence than the loss of the same amount of C from a soil already depleted of C or which started with a smaller total C pool. To account for this a C Pool size Index was computed as:

CPI = Sample total organic C (g kg^{-1}) / Reference total organic C (g kg^{-1})

The loss of labile C is of greater consequence than the loss of non-labile C. The reference vegetation soil was used as the reference. The labile C was considered as the portion of SOC that was oxidized by KMnO4. To account for this, C Lability Index (LI) was computed as:

LI = Lability of C in sample soil / Lability of C in reference soil

Lability of C = POXC (g kg^{-1}) / [SOC (g kg^{-1}) – POXC (g kg^{-1})]

5.2.4 Humic acid extraction and solid-state 13C-Nuclear Magnetic Resonance (NMR) Spectroscopy. Humic acid (HA) in three 8-19 mm aggregate-size class samples from combination of three replicates of RV, CT and NT3 at 0-5 cm soil depth in SbCS was extracted following the method of Swift (1996). Briefly, an oven-dried (40 ºC) and 2 mm-sieved aggregate sample was used for H^+ exchanging by 0.1 M HCl (pH 1–2), and overnight extraction with 0.1 M NaOH (pH 12-13). The supernatant was recovered by centrifugation at 10,000 rpm (25 ºC) for 10 min, and the pH was immediately adjusted to 1.0–1.5 using 6M HCl (1:1 water:acid). The residue was re-extracted and the supernatants were mixed. The acidified suspension was centrifuged at 10,000 rpm (25 ºC) for 10 min and the sediment was re-dissolved with 0.1 M KOH. Then, this solution was made 0.3 M with respect to KCl and the flocculated colloidal particles were recovered by centrifugation at 10,000 rpm (25 ºC) for 10 min. The supernatant was acidified to pH 1 by 6M HCl (1:1 acid:water) and precipitated HA was recovered by centrifugation at 10, 000 rpm (25 ºC) for 10 min. The precipitated HA was re-suspended four times with 0.1 M HCl /0.3 M HF solution for 16 hours. The extract (HA) was purified by dialyzing with Milli-Q water for seven days and then lyophilized.

NMR measurements were performed on a Bruker Avance DRX 400 NMR spectrometer (9.4 T) (Bruker Analytische Messtechnik GmbH, Rheinstetten, Germany). Cross Polarization–Magic Angle Spinning (CP-MAS) pulse sequence was implemented using a standard MAS probe 4 mm at room temperature. HA samples were placed on a Kel-F rotor and were spun at 12 kHz. The CP pulse sequence was accomplished with the contact time value of 1 ms and the time acquisition value of 48 ms. During this time a SPINAL-64 pulse sequence was performed for decoupling process between hydrogen and carbon nuclei (Lee & Goldburg, 1965). A recycle time delay was 0.5 s and the number of scans was 50,000. The spectral window was related by CH_2 carbon (δ_{iso} = 43.5 ppm) of Glycine (Ye, Fu, Hu, Hou, & Ding, 1993).

5.2.5 Statistical analysis. The statistical analysis was performed using SAS 9.2 statistical software. To compare significant effects of tillage and crop rotation treatments of each cropping system at each depth, data were independently subjected to analysis of variance procedures with randomized complete block design, and comparisons among treatment means were computed based on least significant difference test (LSD) at the 0.05 probability level, unless otherwise stated. Correlation coefficients between aggregate-associated SOC over size classes and soil aggregation indices of mean values from the three replicates of CT and NT systems were computed using the CORR procedure of SAS 9.2.

5.3 Results

5.3.1 Distribution of aggregate size classes and soil aggregate indices.

5.3.1.1 Rice-based cropping systems. Tillage and crop rotations did not have a significant effect on macro- and mesoaggregate size distribution at the three depths but CT-Rc had significantly higher amounts of microaggregates than NT-Rc (i.e., NT1-Rc, NT2-Rc, NT3-Rc) in 0-5 and 5-10 cm depths (Table 5.2). Although they did not differ, NT showed an increasing trend of the greater proportion of large macroaggregate (8-19 mm) in 0-5 cm depth. NT-Rc averagely had 23% more proportional distribution of macroaggregates than CT-Rc while soil under CT-Rc tended to increase more meso- and microaggregates than under NT-Rc indicating the disruptive effect of plowing. In general, there were no noticeable changes in soil aggregate size distribution among treatments in 5-10 and 10-20 cm depths. When comparing with RV, cultivated soils had significantly lower large macroaggregates (8-19 mm) at the two surface soil layers but greater meso- and microaggregates were observed in cultivated soils. On average, and across all soil depths, the proportion of 8-19 mm aggregate size fraction was 59%, 43% and 47% in RV, CT-Rc, and NT-Rc, respectively. This proportion decreased with increasing soil depths in both RV and cultivated soils.

The soil under RV was well aggregated and characterized by greater ASI compared with CT-Rc and NT-Rc. Among the cultivated soils, the three NT-Rc treatments had greater ASI than that of CT-Rc. In relation to large macroaggregates, soils under RV had significantly larger MWD and MGD in 0-5 and 5-10 cm depths whereas those under NT-Rc showed increasing trend compared with CT-Rc in 0-5 cm (Table 5.3). Similar values of the three aggregation indices under treated soils were observed in 5-10 and 10-20 cm depths.

5.3.1.2 Soybean-based cropping systems. Tillage and crop rotations significantly affected distribution of large macro, meso- and microaggregates in 0-5 cm depth (Table 5.4). NT1-Sb, NT2-Sb and NT3-Sb had 26%, 42%, and 50%, respectively, greater large macro-aggregates than that of CT-Sb. This higher proportion of large macroaggregates under NT-Sb (i.e., NT1-Sb, NT2-Sb, NT3-Sb) consequently reduced the proportions of meso- and microaggregates. In 5-10 and 10-20 cm depths, the increasing proportions of large macroaggregates under NT were also observed while the distribution of other aggregate size classes among treatments was almost constant. Soils under RV had significantly more large macroaggregates (8-19 mm) that those under CT-Sb and NT1-Sb in 0-5 cm depth. Consequently, the soils under RV had lower amounts of meso- and microaggregates compared with cultivated soils. The proportion of large macroaggregates under the bi-annual rotations (NT2-Sb and NT3-Sb) did not differ from that under RV. This recovery trend signified the importance of NT cropping systems in rotation and association with diversified crop species in re-aggregating the soils. On average, and across all soil depths, the proportions of large macroaggregates was 45% and 53% in CT-Sb and NT1-Sb, respectively, and their levels ranged RV > NT3-Sb > NT2-Sb > NT1-Sb > CT-Sb.

Soils under RV and NT-Sb treatments had larger MWD and MGD compared with CT-Sb in 0-5 cm depth (Table 5.5). They also well aggregated soils compared with CT-Sb as indicated by higher ASI in the surface soil layer. In general, the increasing trend of the three aggregation indices under NT-Sb was also observed in 5-10 and 10-2 cm depths and the significant effects on these aggregation indices might be evident with time due to higher biomass-C inputs and less physical disruption.

5.3.1.3 Cassava-based cropping systems. Adoption of NT management did not significantly affect the proportion of aggregate distribution in all classes and depths except microaggregates in 5-10 and 10-20 cm depths (Table 5.6). On average, an increasing trend of 60% more proportion of large macroaggregates under bi-annual rotations (NT2-Cs and NT3-Cs) over CT-Cs was observed in 0-5 cm depth. This increase in large macroaggregates consequently decreased in meso- and microaggregates in NT-Cs (NT1-Cs, NT2-Cs, NT3-Cs) treatments. CT-Cs significantly increased the proportions of microaggregates over the three NT-Cs treatments at the two subsoil layers. The tendency of having more mesoaggregates in all soil depths and microaggregates in the surface layer also appeared. The soil under RV had more large macroaggregates than CT-Cs and NT1-Cs, resulting in a lower proportion of meso- and microaggregates. The increasing proportions of large macroaggregates by 28% and 29% under NT-Cs treatments compared with CT-Cs were also observed in 5-10 and 10-20 cm depths, respectively. On average, and across all soil depths, the proportion of 8-19 mm size fraction decreased from 59% in soil under RV to 34% and 47% under CT-Cs and NT-Cs, respectively.

Soils under RV had 29% larger MGD than cultivated soils, and 73% and 33% larger MWD than CT-Cs and NT1-Cs, respectively, in 0-5 cm depth. However, MWD and MGD did not differ among RV and treatments in 5-10 and 10-20 cm depths (Table 5.7). Soil under RV aggregated more than CT-Cs as characterized by higher ASI. Even no significant increase in soil aggregation after three-year NT practices compared with CT-Cs, an increasing trend of better aggregation was observed under NT-Cs in all soil depths. On average, and across all soil depths, NT-Cs treatments had 5% more ASI than CT-Cs. The significant improvement of aggregation indices might be evident with time.

5.3.2 Aggregate-associated soil organic C, total N and permanganate oxidizable C, and C management index.

5.3.2.1 Rice-based cropping systems. SOC and total N concentrations associated with aggregates were nearly constant among size classes in all depths except the microaggregates which had higher concentrations than others in 0-5 and 5-10 cm depths. In general, tillage and crop rotations did not significantly affect SOC and N concentrations in all aggregate size classes (Tables 5.8 and 5.9). Even no significant differences, higher values of SOC concentrations were observed in soil under NT-Rc compared with CT-Rc in 0-5 and 5-10 cm depths. The per cent increase in SOC concentrations in the surface layer was greater in the subsoil layer. On average, NT-Rc increased more SOC concentrations than that of CT-Rc by 10%, 9% and 15% in 0-5 cm and by 7%, 6% and 5% in 5-10 cm in macro-, meso-, and microaggregate size classes, respectively. Results of total N concentrations were partially consistent to SOC, which NT-Rc tended to increase more aggregate-associated total N. Although SOC and total N associated with aggregates did not differ, POXC showed a significant difference in all size classes in 0-5 cm depth (Table 5.10). On average, and across all size classes, the bi-annual rotations (NT2-Rc and NT3-Rc) significantly increased 24% POXC greater than that of CT-Rc. NT1-Rc showed greater POXC concentration in 8-19, 4-8 and 1-2 mm aggregate fractions than CT-Rc. The increasing trend of NT-Rc over CT-Rc was also observed in 5-10 and 10-20 cm depths. When comparing to RV, aggregate-associated SOC, total N and POXC concentrations were greater in large macroaggregates and microaggregates in RV soil compared with those in cultivated soils in 0-5 and 5-10 cm depths. Aggregate-associated SOC, total N and POXC concentrations in all aggregate size classes of each depth and treatment were nearly constant.

Based on the results of POXC concentrations, the bi-annual rotations showed greater CMI compared with CT-Rc in all aggregate size classes in 0-5 cm depth and NT1-Rc also had higher CMI in 8-19 and 1-2 mm aggregate fractions (Table 5.11). On average, and across all aggregate size classes, the bi-annual rotation treatments had CMI by 19% greater than CT-Rc. Although they did not differ in the two subsoil layers except 1-2 mm fraction in 10-20 cm depth, the three NT-Rc treatments tended to promote CMI values. On average, and across all aggregate size classes, NT-Rc had higher CMI than that of CT-Rc by 9% and 16% in 5-10 and 10-20 cm depths, respectively.

5.3.2.2 Soybean-based cropping systems. Significant effects of tillage and crop rotations were observed for SOC associated with large macroaggregates in 0-5 and 5-10 cm depths, and 4-8 mm fractions in 0-5 cm depth (Table 5.12). NT3-Sb significantly increased SOC concentrations by 13% and 11% at 0-5 and 5-10 cm depths, respectively. On average, NT-Sb quantitatively increased SOC concentrations by 9%, 4% and 7% in 0-5 cm, by 10%, 12% and 14% at 5-10 cm and by 5%, 8% and 10% at 10-20 cm in macro-, meso-, and microaggregate size classes, respectively, compared with CT-Sb. Similarly, significant effects on aggregate-associated total N were detected in 0.053-0.25 mm in 0-5 cm, 8-19 mm in 5-10 cm and 8-19 and 4-8 mm aggregate fractions in 10-20 cm depth (Table 5.13). The per cent increase in total N concentrations under NT-Sb was greater than SOC. On average, and across all aggregate size classes, NT-Sb soils had more total N concentrations by 12%, 19% and 11% compared with CT-Sb in 0-5, 5-10, and 10-20 cm depths, respectively. Similar to SOC, POXC concentrations differed among treated soils in 8-19 and 4-8 mm aggregate size classes in 0-5 cm depth (Table 5.14). The three NT-Sb treatments averagely accumulated 25% and 22% greater POXC concentrations than those of CT-Sb in 8-19 and 4-8 mm fractions. On average, and across all aggregate size classes, NT-Sb soils accumulated more aggregate-associated POXC by 20%, 9% and 17% compared with CT-Sb in 0-5, 5-10, and 10-20 soil depths, respectively. Although, they did not differ in the two subsoil layers, significant differences might be evident with time since higher biomass-C inputs under NT-Sb were continuously added to the soils. In general, RV soils had greater aggregate-associated SOC, total N and POXC concentrations in large macro- and microaggregate size classes in 0-5 cm depth compared with those of cultivated soils. On average, RV had greater SOC by 31% and 60%, total N by 43% and 82%, and POXC by 25% and 59% in large macro- and microaggregates, respectively.

In relation to POXC concentrations, NT-Sb averagely increased CMI by 26% and 24% in 8-19 and 4-8 mm aggregate size classes, respectively, in 0-5 cm depth (Table 5.15). CMI values also tended to be promoted by the adoption of NT practices in rotation or association with diversified cover crop species in the subsoil layers. On average, and across all aggregate size classes, NT-Sb had higher CMI values than those of CT-Sb by 22%, 8%, and 17% in 0-5, 5-10, and 10-20 cm depths, respectively. The bi-annual rotation treatments were likely to promote more CMI than NT1-Sb.

5.3.2.3 Cassava-based cropping systems. Similar to RcCS, tillage and crop rotations did not significantly affect the concentrations of SOC and total N in all aggregate size classes and depths (Tables 5.16 and 5.17). Although they did not differ, soils under NT practices tended to increase more SOC and total N concentrations in all depths. On average, soils under NT-Cs accumulated higher SOC than CT-Cs by 6%, 5% and 5% at 0-5 cm, by 4%, 3% and 3% at 5-10 cm, and by 7%, 13% and 16% at 10-20 cm depths in macro-, meso-, and microaggregate size classes, respectively. Total N concentrations resulted in similar increasing trend. On average, and across all size classes, soils under NT-Cs had 15%, 7%, and 6% more total N concentrations than those under CT-Cs in 0-5, 5-10, and 10-20 cm depths, respectively. Unlike SOC and total N, POXC concentrations in most aggregate size classes in 0-5 cm depth were increased in NT-Cs (Table 5.18) while bi-annual rotations showed a greater increasing trend compared with NT1-Cs. On average, and across all size classes, bi-annual rotation treatments had 20% greater POXC concentrations than that of CT-Cs. The increasing trend was also observed in the two subsoil layers, in which NT-Cs had 16% and 27% more POXC concentrations compared with those of CT-Cs in 5-10 and 10-20 cm depths. The concentrations of SOC, total N and POXC were nearly constant in all aggregate size classes. In general, soils under RV accumulated greater SOC, total N and POXC concentrations than cultivated soils in large macroaggregates in 0-5 cm depth and in microaggregates in 0-5 and 5-10 cm depths.

Similar to RcCS, bi-annual rotations significantly increased CMI in all aggregate size classes, except 2-4 mm, in 0-5 cm depth (Table 5.19). On average, and across all size classes, the bi-annual rotation treatments promoted 22% greater CMI than that of CT-Cs. Although significant differences did not exist, NT1-Cs promoted 5% more CMI values than CT-Cs. The increasing trend of CMI under NT practices was also observed in the two subsoil layers. On average, and across all aggregate size classes, NT-Cs had higher CMI than that of CT-Cs by 17% and 29% in 5-10 and 10-20 cm depths, respectively.

5.3.3 Relations between SOC associated with aggregate size classes and soil aggregate indices. Table 5.20 showed significantly positive correlations ($P \leq 0.05$) between SOC associated with large and smallest macroaggregates (8-19 and 2-4 mm, respectively) and the three soil aggregation indices in 0-5 cm depth in RcCS. Similarly, the three soil aggregation indices in SbCS positively correlated to large macroaggregate-associated SOC (Table 5.21). In addition, MWD and MGD of the smallest macroaggregate in 0-5 cm depth and microaggregates in 5-10 cm depth were also positively correlated to their associated SOC. CsCS showed positive correlations between soil aggregation indices and SOC associated with most aggregate size classes in 0-5 cm depth, and between ASI and microaggregate-associated SOC in 10-20 cm depth (Table 5.22). SOC associated with large and second large macroaggregates (8-19 and 4-8 mm, respectively) positively correlated ($P \leq 0.01$) to the three soil aggregation indices except MGD of second large macroaggregates ($P \leq 0.05$). The positive correlations ($P \leq 0.05$) were also observed in the smallest macro- and mesoaggregates except MGD of the 1-2 mm aggregate size class. The presence of positive correlations between soil aggregation indices and the SOC associated with the large macroaggregate size class in the three cropping systems could be evident that the increased proportions of large macroaggregates after the adoption of NT systems in rotation or association with diversified crop species could partially restore SOC in the surface soil layer and potentially in the subsurface layers.

5.3.4 Solid-state 13C-Nuclear Magnetic Resonance spectroscopy of humic acid. The HA ^{13}C CP-MAS NMR spectra of 8-19 mm soil aggregate size class of RV, CT and NT in 0-5 cm depth are shown in Figure 5.1 which represented the intensities of ^{13}C signals of HAs. The HA signals are divided into seven main chemical shift ranges: 0-45, 45-65, 65-90, 90-110, 110-143, 143-160, and 160-188 ppm. In the aliphatic region (0-110 ppm) is dominated by the peaks at 25 and 30 ppm for alkyl C, 56 ppm for methoxyl C which overlaps with intensity derived from N-alkyl, 71 ppm for O-alkyl C and 102 ppm for anomeric C. Apart from this, the aromatic (110-143 ppm) and phenolic (143-160 ppm) regions are dominated by the peaks at 129 and 151 ppm coming from aromatic C and the phenolic C, respectively. The presence of carboxyl C with a maximum peak at 173 ppm was also noted in the carboxylic region (160-188 ppm). There were no major differences in term of presence of specific peaks in the three land uses. However, the signal intensity contribution of the chemical groups can be obtained. HA from RV showed higher signal intensities of aliphatic and carboxylic chemical groups than those from CT and NT. In general, HA from NT tended to have higher signal intensities of the aliphatic group, particularly O-alkyl C than that from CT. In contrast, higher signal intensities of the aromatic group in HA from CT than those from NT and RV were detected. The levels of the signal intensities of the aromatic group ranged CT > NT > RV. This characteristic indicates that aliphatic and carboxylic components were naturally transformed into aromatic components as a result of land manipulation.

5.4 Discussion

5.4.1 Effect of conservation agriculture on size distribution of water stable aggregates and soil aggregation indices. Soil aggregate stability is dependent on texture, clay mineralogy, exchangeable ions, aluminum and iron oxides, SOC concentration and microbial activities (Bronick & Lal, 2005; Kay, 1998) and changes in agricultural management practices (i.e., tillage practices and crop rotations) rapidly influence the proportional distribution of soil water stable aggregates (Angers et al., 1992). Castro Filho et al. (2002) suggested the use of 19 mm sieve to homogenize soil samples before wet-sieving because the use of smaller sizes of sieves underestimates the actual ability of NT to form large stable aggregates. In the present study, NT systems in RcCS, SbCS and CsCS increased the proportion of large macroaggregates compared with CT systems. Stable large macroaggregates (8-19 mm) generally dominated aggregate distribution in soils under both CT and NT practices. Previous work on comparison of CT and NT effects concentrated on the proportions of stable macroaggregates with smaller than 8 mm size classes or even smaller but very few studies have compared 8-19 mm size classes. The high proportions of stable large macroaggregates in clayed soils were also reported in the other studies in the tropical and subtropical climates (Madari et al., 2005; Tivet, Sá, Lal, Briedis, et al., 2013). The increase in the large macroaggregate proportion under NT consequently led to lower meso- and microaggregate proportions. Since CT contained more proportions of meso- and microaggregates than did NT, there could be a greater risk of aggregate-associated SOC, total N and POXC from CT soils.

Soil aggregation is one of important mechanisms to protect and consequently to sequester SOC (Feller & Beare, 1997; Lützow et al., 2006). The process of soil aggregation under NT systems with continuous biomass-C inputs depends on an increase in aggregating agents such as fungal hyphae, microbial bi-products (Haynes & Francis, 1993) and root exudates (Guggenberger et al., 1999) and a decrease in physical disruption of macroaggregates (Barto, Alt, Oelmann, Wilcke, & Rillig, 2010). Although NT practices did not lead to a significant increase in MWD, MGD and ASI compared with those of CT in RcCS and CsCS in this study except ASI in RcCS, soils under NT consistently showed higher proportion of large macroaggregates leading to larger MWD and MGD and higher ASI in the surface soil layer especially. These increasing trends might be also evident in the subsurface soil layers over time since it was already apparent in SbCS. The possible contributing factor could be the continuous greater supply of biomass-C through high cropping intensity systems providing aggregate binding agents and the absence of physical disruption in the NT systems that might influence the increase in soil macro-aggregation. Additionally, the increase in roots from diversified crop species under NT are also involved in macroaggregate stabilization (Tisdall & Oades, 1982). It was obvious that SOC concentrations associated with large macroaggregates positively correlated with the three soil aggregation indices in the surface soil layer in the three cropping systems. Tivet, Sá, Lal, Briedis, et al. (2013) found a significant increase in large macroaggregate fractions and labile SOC under eight-year NT systems with diversified crop species rotations and a positive correlation between soil aggregation indices (i.e., MWD, MGD, ASI) and labile fractions of SOC. Hok et al. (under review) evaluated the changes in total SOC concentrations in the same experiment. They reported that soils under NT had higher SOC than those of CT in SbCS and CsCS but did not find a significant difference in RcCS. This could partially be contributed by this higher large macro-aggregation in soils under NT.

Macro- and mesoaggregate fractions might also positively correlate with clay plus fine silts. In general, there is less effect of SOC on soil aggregation in highly weathered soils of the tropics because iron and aluminum oxides and 1:1 clay minerals are the dominant binding agents in oxide-rich soils (Oades & Waters, 1991; Six et al., 2002). Hok et al. (under review) reported that this studied soil was Oxisols and dominated by kaolinite, and the clay plus silt contents in all depths were nearly constant in all treatments and depths and represented ~ 99%. Amézketa (1999) reviewed that the inorganic stabilizing agents including clays, polyvalent metal cations such as Ca^{2+}, Fe^{3+}, and Al^{3+}, oxides and hydroxides of Fe and Al, calcium and magnesium carbonates and gypsum positively affect soil aggregate formation and stabilization. Thus, these major factors mentioned above could partially contribute to the slow effects of short-term NT practices with high and diversified biomass-C inputs in RcCS and CsCS on enhancement of macroaggregate formation and aggregation indices over CT that could lead to a significant increase in the present study. It partially corroborates with Tivet, Sá, Lal, Milori, et al. (2013) who concluded that main aggregating agents in Oxisols are not only clay and oxides contents but also the constant (rizho) deposition of organic matter, which maintains the binding effect and increases the proportion of water stable aggregates based on the results of SOC and H_{LIF} distribution among aggregate size classes in their study. Thus, the significant changes might be detected with time due to the continuous provision of biomass-C as aggregate binding agents from crop residues under NT.

5.4.2 Effect of conservation agriculture on aggregate-associated SOC, total N and POXC. The soil stability can be positively related to the proportions of large macroaggregates, normally containing most of C in the soil (Six et al., 2004). SOC sequestration increase in tropical soils is influenced by NT cropping systems in rotation or association with cover crops due to the absence of physical soil disruption and continuous biomass-C inputs (Bayer, Martin-Neto, et al., 2006; Neto et al., 2010; Sá et al., 2013). The formation of macroaggregates increases SOC sequestration because SOC can be protected by occlusion in soil aggregates (Lützow et al., 2006; Mikutta et al., 2006; Six et al., 2000; Tivet, Sá, Lal, Briedis, et al., 2013). The positive correlation between SOC concentrations and large macroaggregate (8-19 mm) formation in the tropical and subtropical climate were previously reported (Briedis, Sá, Caires, Navarro, et al., 2012; Madari et al., 2005; Tivet, Sá, Lal, Briedis, et al., 2013). Thus, the enhancement of stable large macroaggregates may lead to an increase in the ability of soil to sequester SOC. In the present study, accumulated SOC within large macroaggregates under CT decreased mainly in the 0-5 cm depth compared with NT in the three cropping systems. This was probably due to the presence of CT that reduced the proportion of large macroaggregates (8-19 mm) which may explain lower SOC concentrations. The decrease was also observed in other macro- and mesoaggregate fractions. The continuous CT destroys soil aggregates (Zotarelli et al., 2007) and consequently increases soil aeration that stimulates soil microbial biomass and activity (D. Guo et al., 2013), thus hastening SOC oxidation (Green et al., 2007; Jastrow et al., 1996; Reicosky et al., 1995), which resulted in the decreased SOC. In the majority of smaller aggregate size classes, NT treatments also resulted in higher aggregate-associated SOC in the three cropping systems.

This could be a partial consequence of lower total SOC in bulk soils under CT as Hok et al. (under review) reported that NT practices had higher SOC than those of CT in SbCS and CsCS but not RcCS in the same experiment.

The intensified cropping sequence under NT provided continuous biomass-C inputs to maintain the C flow in the soil that could enhance the process of soil aggregation and C transformations. It is quite consistent that SOC associated with macroaggregates were slightly higher than those with mesoaggregates in the three cropping systems. This behavior could be probably explained by the concept of aggregate hierarchy (Oades, 1984; Tisdall & Oades, 1982) which stated that organic matter within large macroaggregates tends to be higher than that in smaller aggregates because fresh organic matter is the precursor in macroaggregate formation. As a result of high accumulation of crop residues in the soil surface under NT, the fresh crop residues are easily accessible by soil microorganisms for metabolism process and sometimes even more than their capacity to metabolize them, which leads to a great input of metabolizable organic compounds into SOM (Bayer et al., 2002). Examination of CP-MAS ^{13}C NRM data of studied soils from the large macroaggregate in the surface layer illustrated that HA from NT soil tended to have higher signal intensities of aliphatic C (0-110 ppm) than that from CT, especially O-alkyl C which was derived from crop residues returned to the soil. In contrast, SOC associated with microaggregates was likely to be higher than that with mesoaggregates but comparable to macroaggregates. Microaggregates play an important role in SOC sequestration (Jastrow et al., 1996). This microaggregate-associated SOC is more stable than that in macroaggregates because they have more reactive surface area due to an increase in clay and sesquioxides and are physically protected with microaggregates (Barthès et al., 2008; Feller & Beare, 1997). The formation of microaggregate within macroaggregates is crucial to SOC storage and stabilization

(Six et al., 2000; Tivet, Sá, Lal, Briedis, et al., 2013) due to the physical protection within macroaggregates.

The continuous supply of high aboveground crop residues and root biomass via the incorporation of deep rooting forage species into crop rotations supplied greater fresh C in NT than CT systems leading to increased microbial activities (Lienhard et al., 2013). Consequently, SOC decomposition rates increase. The microbes are also able to decompose the native C or recalcitrant C compounds with their enzymes using fresh C as a source of energy (Fontaine et al., 2007). During the six-month dry season in this study, no cover crops were planted in CT plots while the permanent organic soil cover was maintained in the NT plots. The latter might consequently increase the humification process of native C attaining more advanced stages, with a relative decrease of the concentration of more recalcitrant organic compounds. The CP-MAS ^{13}C NRM data of the studied soils from large macroaggregate in the surface layer revealed that HA from CT had higher signal intensities of aromatic C (110-143 ppm) than those of NT and RV in 0-5 cm soil layer. This also contributes to the finding of slow effect of intensified NT crop rotations with diverse cover crop species on total SOC compared with CT as reported by Hok et al. (under review) at the same experiment. When comparing with RV, it is evident that HA extracted from cultivated soils had higher proportions of aromatic C than RV. The order levels of aromatic C were CT > NT > RV. This finding was similar to those reported by González Pérez et al. (2004). They found that HAs from the non-cultivated and NT/maize-cajanus soils (i.e., bulk soils) of subtropical Oxisols had less concentration of aromatic C than that from CT, shown by CP-MAS ^{13}C NRM, electron paramagnetic resonance (EPR), and Fourier transform infrared (FTIR). Similarly, Mahieu, Randall, and Powlson (1999) also reported that HAs from cultivated soils had higher concentration of aromatic C than those from non-cultivated soils determined by CP-MAS ^{13}C NRM.

It has been known that grass and legume cover crops act as a source of supplement N to the soil (Wagger et al., 1998) so soil N can be increased with an increase in the amount of residue returned to the soil (Ghimire et al., 2012). In the present study, aggregate-associated total N in the majority of aggregate size classes under NT in all depths in the three cropping systems showed an increasing trend while its significant increase in some aggregate size classes were already detected. This result is reflective of the differing amounts of above- and belowground crop biomass inputs and types of crop residues returned to the soil leading to increased total N concentrations. Consequently, the soil aggregation under NT is promoted due to increased microbial biomass and activities which in turn synthesizes polymers that act as aggregating agents (Jastrow et al., 1996). Tivet, Sá, Lal, Briedis, et al. (2013) reported that the inclusion of grass and legumes as cover/relay crops in NT crop rotations highly produced monosaccharide (i.e., arabinose and xylose) that could directly or indirectly enhance soil aggregation through their influence on soil microbes. The absence of soil physical disruption under NT might also contribute to the increased N because the mechanical soil disturbance by CT operations might allow N released from crop residues to be mineralized more rapidly due to lack of physical protection. Our results showed a higher accumulation of aggregate-associated total N in most aggregate size classes under NT compared with those under CT, which coincided with Six et al. (2002) who reviewed that N is protected against mineralization within aggregates. The increased N mineralization in tropical and temperate soils exists when the aggregate structure is disrupted. The N stabilization within aggregates is partly related to the decrease in oxygen concentration in the center of soil aggregates. The N distribution patterns in aggregate size classes were similar across the three cropping systems, with macro and microaggregates having higher concentrations than mesoaggregates. These results indicate the importance of stable macroaggregates and total N associated with microaggregates in N retention. Even higher N concentrations in microaggregates, they do not reflect the greater N stocks in the soils based on a mass basis. In general, the proportions of macroaggregates were very much greater than those of microaggregates.

POXC is a labile SOC pool that is sensitive to short-term land use changes and correlates with SMBC, soluble carbohydrate C and total C (Melero et al., 2009; Weil et al., 2003). The changes in labile SOC pool can be served as an indicator of future changes in total SOC. Soil aggregate stability positively correlated to residue restitution and fungal and bacterial densities under NT systems (Lienhard et al., 2013), and POXC (Stine & Weil, 2002). The greater biomass-C inputs that increased POXC under NT systems maybe consequently enhance soil macroaggregate formation which may protect SOC. Although the continuity of C supply through crop residues under NT did not lead to a significant increase in aggregate-associated SOC compared with CT after three years in RcCS and CsCS, it is obvious that NT in the three cropping systems significantly increased concentrations of POXC associated with the large macroaggregates and also with most other size classes in RcCS and CsCS compared with CT in 0-5 cm depth. The possible explanation for the high POXC concentrations under NT was probably due to the higher fresh organic matter inputs from the diverse crop residues included in the crop associations or rotations as shown in the CP-MAS ^{13}C NRM data in Fig. 1 that indicates higher signal intensities of aliphatic C under NT than that under CT, the absence of soil physical disruption that exposed young SOC to microbial oxidation and the increased proportions of large macroaggregates that could be formed around the fresh C obtained from the crop residue returned to the soil. Tivet, Sá, Lal, Briedis, et al. (2013) reported the recently deposited labile SOC (i.e., particulate organic C, hot-water extractable C and total polysaccharides) can be potentially protected in large macroaggregates (8-19 mm) and the labile SOC fractions positively correlated to SOC concentrations in aggregate size classes. The consistent effect of NT in rotation or association with diversified cover crop species on POXC in this study suggests that this labile SOC pool may be a good indicator to assess SOC dynamics within aggregates in short-term soil management practices and to estimate long-term trends. These increased POXC concentrations within large macroaggregates under NT led to greater CMI compared with CT due to an increase in the lability of SOC in the surface soils in the three cropping systems. These findings suggest that labile SOC is restored faster than SOC associated with aggregates especially in the large macroaggregates, indicating the potential of NT systems to rehabilitate the soil quality and to sequester SOC through enhancement of macro-aggregation that can stabilize SOC within macroaggregate-occluded microaggregates. The increasing trend of aggregate-associated POXC accumulation under NT also showed the two subsurface soil layers. This probably resulted from the rate of biomass-C inputs from crop residues retained on the soil surface, which create a positive C budget, accentuate C transformation and support a continuous flow of biomass which releases organic compounds (Sá et al., 2013), the incorporation of deep-rooting cover crops such as Congo grass, sorghum, millet, stylo and sunhemp that could provide root biomass and exudates, and less soil aggregate disruption leading to decreased oxidation of this labile SOC.

5.5 Conclusions

Conversion of RV to cultivated land dramatically influenced the distribution of aggregate size classes, soil aggregation indices and aggregate-associated SOC, total N and POXC in the two surface layers. The aggregate stability depends primarily on the formation of large macroaggregates (8-19 mm) which dominated aggregate size distribution with relatively higher proportions under RV and NT than CT. The soil aggregation indices positively correlated with the large macroaggregate-associated SOC. Large macroaggregates which plays an important role in storage and stabilization of SOC, total N and POXC within macroaggregate-occluded microaggregates are disrupted by the continuous CT. Reduction in physical disruption combined with crop residue retention in the soil surface within three years of this study significantly increased the SOC retained in the large macroaggregates of the top soil in CsCS and showed a recovery trend in RcCS and SbCS due to greater aggregate stability. The labile SOC (i.e., POXC) was more sensitive to this short-term change of agricultural management practices than total SOC resulting in a significant increase in its concentration in the majority of aggregate size classes under NT compared with CT in the soil surface layer and consequently promoting CMI. The results of CP-MAS ^{13}C NRM measurement suggest that the continuous biomass-C inputs via crop residues under NT tended to increase the proportions of aliphatic C than under CT while in reverse for aromatic C. Among NT systems, the bi-annual crop rotations in the three cropping systems tended to be more effective than one year frequency pattern in enhancing large macro-aggregation and restoring the concentrations of SOC, total N and POXC associated with large macroaggregates. Thus, they might be served as the appropriate crop rotation scheme to maximize SOC, total N and POXC retention in the surface soil and a potential restoration in the subsurface soil layers in a longer period as a result of continuity of high biomass-C inputs.

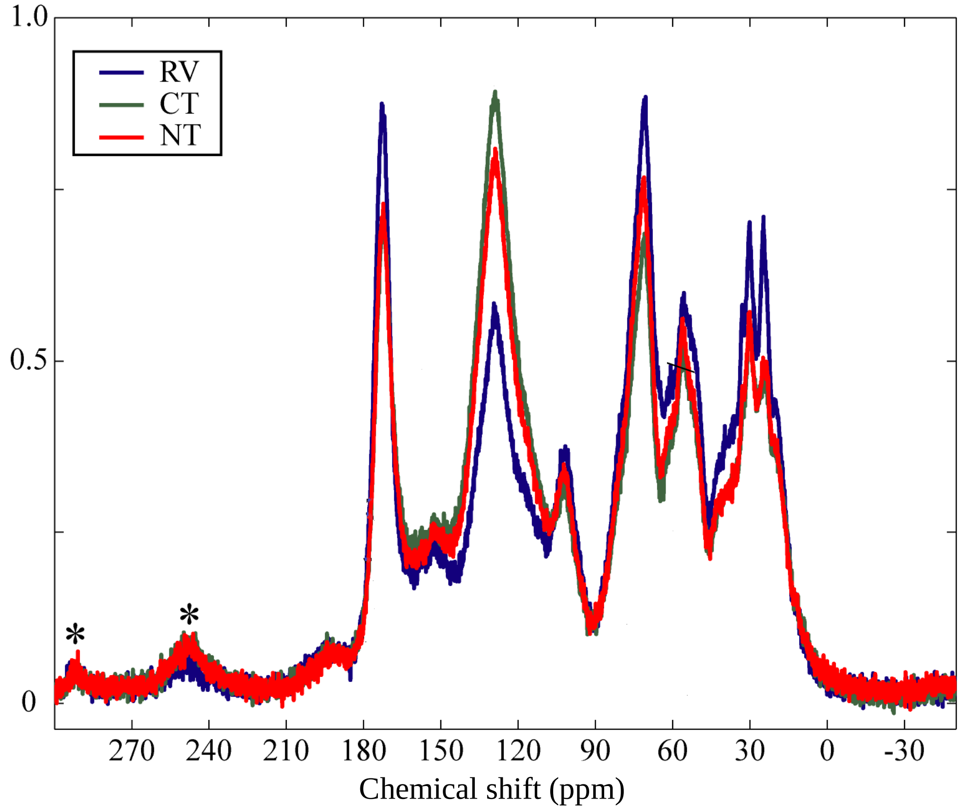


Figure 5.1. CP/MAS 13C NMR spectra of humic acids extracted from large soil macroaggregates (8-19 mm) under reference vegetation (RV), conventional tillage (CT) and no-till (NT) in 0-5 cm depth.

Table 5.1

Land use, crop sequence, and C input in the three-year experiment period (2009-2011)

Land use	Crop sequence	C input (Mg ha^{-1}) Cumulative	Annual
Rice-based cropping systems			
CT-Rc	Mb/Rc – Mb/Rc – Mb/Rc	6.27	2.09
NT1-Rc	Mt/Rc+St – Mt+Cr/Rc+St – St(2010)[¥]/Rc+St	18.83	6.28
NT2-Rc	Mt/Rc+St–Mt+Cr+St (2009)/Mz+St–Mt+Cr+St (2010)/Rc+St	16.64	5.55
NT3-Rc	Mt/Mz+St – Mt+Cr+St (2009)/Rc+St – St (2010)/Mz+St	16.65	5.55
Soybean-based cropping systems			
CT-Sb	Se/Sb – Se/Sb – Se/Sb	4.92	1.64
NT1-Sb	Mt/Sb+Brz – Brz(2009)/Sb+St – Mt/Sb+St+Sg	18.42	6.14
NT2-Sb	Mt+/Sb+St – Mt+Cr+St (2009)/Mz+St – Mt/Sb+St	21.96	7.32
NT3-Sb	Mt/Mz+Brz – Mt/Sb+St – Mt+Cr/Mz+St	21.87	7.29
Cassava-based cropping systems			
CT-Cs	Cs – Cs – Cs	4.08	1.36
NT1-Cs	Cs+St – Cs+St – Cs+St	12.42	4.14
NT2-Cs	Cs+St – Mt+St (2009)/Mz+St – St (2010)/Cs+St	13.73	4.58
NT3-Cs	Mt/Mz+St – Cs+St – Mt+Cr+St (2010)/Mz+St	15.35	5.12

Mb: mung bean (*Vigna radiata*); Rc: rice (*Oryza sativa* L.); Mt: millet (*Pennisetum typhoides* Burm); St: *Stylosanthes guianensis*; Cr: *Crotalaria juncea*; Mz: maize (*Zea mays* L.); Se: sesame (*Sesamum indicum*); Sb: soybean (*Glycine max* (L.) Merr.); Brz: *Brachiaria ruziziensis* cv. ruzi; Cs: cassava (*Manihot esculenta*); Sg: sorghum (*Sorghum bicolor* L.) [¥] St (*Stylosanthes guianensis)* left from the year in brackets. "/" indicates relay cropping with varying planting dates; "+" indicates crops planted in association (same or staggered sowing dates).

Table 5.2

Distribution of aggregate size classes (g soil in aggregate fraction kg^{-1} soil) in reference vegetation (RV) and different treatments in rice-based cropping systems

Depth		Aggregate size classes (mm)						
(cm)	Land use	8–19	4–8	2–4	1–2	0.5–1	0.25–0.5	0.053–0.25
0–5	RV[a]	718 A	99 ns	64 ns	34 B	25 C	22 C	16 C
	CT-Rc[b]	478 Cns	104	76	83 Ans	105 Ans	60 Ans	49 Aa
	NT1-Rc	561 BC	100	80	78 A	79 AB	46 AB	33 Bb
	NT2-Rc	607 AB	107	78	68 A	59 BC	32 BC	23 BCb
	NT3-Rc	601 B	94	71	66 A	72 AB	42 B	31 Bb
5–10	RV	619 A	119 ns	98 ns	58 B	44 B	27 B	17 C
	CT-Rc	474 Bns	123	81	88 ABns	90 Ans	61 Ans	40 Aa
	NT1-Rc	463 B	113	99	111 A	105 A	50 A	34 Bb
	NT2-Rc	478 B	101	105	109 A	99 A	48 A	34 Bb
	NT3-Rc	454 B	112	110	106 A	96 A	56 A	42 Aa
10–20	RV	424 ns	129 ns	136 ns	113 ns	97 ns	53 ns	32 ns
	CT-Rc	325	113	131	150	134	65	50
	NT1-Rc	319	116	140	155	132	67	42
	NT2-Rc	369	136	141	132	99	58	41
	NT3-Rc	321	141	149	128	121	71	48

Note. RV: reference vegetation; CT: conventional tillage; NT: no-till; Rc: rice; [a] Comparison between tillage systems CT-Rc, NT1-Rc, NT2-Rc, NT3-Rc and RV; Uppercase letters within the same column in each aggregate size class of each depth in each cropping system indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison among tillage systems CT-Rc, NT1-Rc, NT2-Rc and NT3-Rc; Lowercase letters within the same column indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 5.3

Mean weight diameter (MWD), mean geometric diameter (MGD) and aggregate stability index (ASI) in reference vegetation (RV) and different treatments in rice-based cropping systems

	Depth (cm)								
	0-5			5-10			10-20		
Land Use	MWD (mm)	MGD (mm)	ASI (%)	MWD (mm)	MGD (mm)	ASI (%)	MWD (mm)	MGD (mm)	ASI (%)
RV[a]	10.56 A	2.46 A	98.2 A	9.49 A	2.27 A	98.0 A	7.17 ns	1.84 ns	95.3 ns
CT-Rc[b]	7.54 Cns	1.82 Cns	92.8 Cb	7.62 Bns	1.86 Bns	94.1 Bns	5.82	1.61	90.4
NT1-Rc	8.61 BC	2.04 BC	95.5 Ba	7.50 B	1.87 B	94.7 B	5.78	1.61	92.4
NT2-Rc	9.24 B	2.19 B	97.1 ABa	7.63 B	1.89 B	94.9 B	6.52	1.73	93.7
NT3-Rc	9.07 B	2.12 B	96.0 Ba	7.39 B	1.83 B	93.9 B	5.95	1.63	92.3

RV: reference vegetation; CT: conventional tillage; NT: no-till; Rc: rice; [a] Comparison between tillage systems CT, NT1, NT2, NT3 and RV; Uppercase letters within the same column in each aggregate size class of each depth in each cropping system indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison among tillage systems CT, NT1, NT2 and NT3; Lowercase letters within the same column indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 5.4

Distribution of aggregate size classes (g soil in aggregate fraction kg^{-1} soil) in reference vegetation (RV) and different treatments in soybean-based cropping systems

Depth (cm)	Land use	Aggregate size classes (mm)						
		8–19	4–8	2–4	1–2	0.5–1	0.25–0.5	0.053–0.25
0–5	RV[a]	718 A	99 ns	64 ns	34 D	25 C	22 C	16 C
	CT-Sb[b]	464 Cc	79	69	103 Aa	111 Aa	74 Aa	60 Aa
	NT1-Sb	584 Bb	84	78	74 Bb	72 Bb	52 Bab	35 Bb
	NT2-Sb	659 ABab	79	67	60 BCbc	57 Bb	32 BCbc	23 BCb
	NT3-Sb	694 Aa	77	58	48 CDc	46 BCb	29 Cc	24 BCb
5–10	RV	619 ns	119 A	98 ns	58 ns	44 ns	27 ns	17 ns
	CT-Sb	491	101 Bns	88	98	99	50	38
	NT1-Sb	510	100 B	92	102	95	48	29
	NT2-Sb	488	90 B	98	98	100	65	37
	NT3-Sb	536	97 B	86	87	90	47	33
10–20	RV	424 ns	129 ns	136 ns	113 ns	97 ns	53 ns	32 ns
	CT-Sb	384	118	125	124	109	72	38
	NT1-Sb	438	116	114	109	105	58	37
	NT2-Sb	401	110	135	124	107	68	37
	NT3-Sb	472	131	104	99	88	49	38

RV: reference vegetation; CT: conventional tillage; NT: no-till; Sb: soybean; [a] Comparison between tillage systems CT-Sb, NT1-Sb, NT2-Sb, NT3-Sb and RV; Uppercase letters within the same column in each aggregate size class of each depth in each cropping system indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison among tillage systems CT-Sb, NT1-Sb, NT2-Sb and NT3-Sb; Lowercase letters within the same column indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 5.5

Mean weight diameter (MWD), mean geometric diameter (MGD) and aggregate stability index (ASI) in reference vegetation (RV) and different treatments in soybean-based cropping systems

	Depth (cm)								
	0-5			5-10			10-20		
Land use	MWD (mm)	MGD (mm)	ASI (%)	MWD (mm)	MGD (mm)	ASI (%)	MWD (mm)	MGD (mm)	ASI (%)
RV[a]	10.56 A	2.46 A	98.2 A	9.49 ns	2.27 ns	98.0 ns	7.17 ns	1.84 ns	95.3 ns
CT-Sb[b]	7.21 Cc	1.73 Dc	90.4 Cb	7.75	1.88	94.4	6.56	1.70	94.1
NT1-Sb	8.81 Bb	2.06 Cb	95.2 Ba	8.01	1.95	95.8	7.22	1.82	94.4
NT2-Sb	9.72 ABab	2.25 Ba	97.2 ABa	7.68	1.87	94.3	6.77	1.74	94.3
NT3-Sb	10.13 Aa	2.33 ABa	97.1 ABa	8.30	1.99	95.3	7.72	1.92	94.4

RV: reference vegetation; CT: conventional tillage; NT: no-till; Sb: soybean; [a] Comparison between tillage systems CT, NT1, NT2, NT3 and RV; Uppercase letters within the same column in each aggregate size class of each depth in each cropping system indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison among tillage systems CT, NT1, NT2 and NT3; Lowercase letters within the same column indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 5.6

Distribution of aggregate size classes (g soil in aggregate fraction kg^{-1} soil) in reference vegetation (RV) and different treatments in cassava-based cropping systems

Depth (cm)	Land use	Aggregate size classes (mm)						
		8–19	4–8	2–4	1–2	0.5–1	0.25–0.5	0.053–0.25
0–5	RV[a]	718 A	99 ns	64 ns	34 C	25 C	22 C	16 C
	CT-Cs[b]	363 Cns	97	97	134 Ans	147 Ans	79 Ans	52 Ans
	NT1-Cs	509 BC	94	82	94 AB	102 AB	59 AB	43 AB
	NT2-Cs	579 AB	103	80	75 BC	75 BC	40 BC	30 BC
	NT3-Cs	581 AB	91	66	78 BC	86 B	48 B	37 B
5–10	RV	619 ns	119 ns	98 ns	58 ns	44 ns	27 B	17 C
	CT-Cs	371	98	85	112	157	83 Ans	55 Aa
	NT1-Cs	466	104	93	105	118	58 A	37 Bb
	NT2-Cs	464	108	101	114	110	55 AB	31 Bb
	NT3-Cs	494	102	90	93	106	58 A	41 Bab
10–20	RV	424 ns	129 ns	136 ns	113 ns	97 ns	53 ns	32 B
	CT-Cs	291	91	113	161	180	83	51 Aa
	NT1-Cs	376	137	130	134	112	54	36 Bb
	NT2-Cs	392	147	126	120	111	54	34 Bb
	NT3-Cs	361	109	117	150	138	69	40 Bab

RV: reference vegetation; CT: conventional tillage; NT: no-till; Cs: cassava; [a] Comparison between tillage systems CT-Cs, NT1-Cs, NT2-Cs, NT3-Cs and RV; Uppercase letters within the same column in each aggregate size class of each depth in each cropping system indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison among tillage systems CT-Cs, NT1-Cs, NT2-Cs and NT3-Cs; Lowercase letters within the same column indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 5.7

Mean weight diameter (MWD), mean geometric diameter (MGD) and aggregate stability index (ASI) in reference vegetation (RV) and different treatments in cassava-based cropping systems

	Depth (cm)								
	0-5			5-10			10-20		
Land use	MWD (mm)	MGD (mm)	ASI (%)	MWD (mm)	MGD (mm)	ASI (%)	MWD (mm)	MGD (mm)	ASI (%)
RV[a]	10.56 A	2.46 A	98.2 A	949 ns	2.27 ns	98.0 A	7.17 ns	1.84 ns	95.3 A
CT-Cs[b]	6.12 C ns	1.60 Cns	90.9 C ns	6.18	1.59	90.4 Cns	5.22	1.48	89.0 Bns
NT1-Cs	7.92 BC	1.89 BC	93.6 BC	7.46	1.84	94.2 B	6.60	1.74	94.4 A
NT2-Cs	8.87 AB	2.09 B	96.1 AB	7.49	1.87	95.2 AB	6.84	1.78	94.9 A
NT3-Cs	8.79 AB	2.04 B	95.0 AB	7.79	1.87	93.9 BC	6.24	1.66	92.9 AB

RV: reference vegetation; CT: conventional tillage; NT: no-till; Cs: cassava; [a] Comparison between tillage systems CT, NT1, NT2, NT3 and RV; Uppercase letters within the same column in each aggregate size class of each depth in each cropping system indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison among tillage systems CT, NT1, NT2 and NT3; Lowercase letters within the same column indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 5.8

Concentrations of aggregate-associated SOC (g kg^{-1}) in aggregate size classes under rice-based cropping systems

Depth (cm)	Land use	Aggregate size classes (mm)						
		8–19	4–8	2–4	1–2	0.5–1	0.25–0.5	0.053–0.25
0–5	RV[a]	26.2 A	23.5 ns	21.9 ns	21.3 ns	21.5 ns	23.4 ns	29.3 A
	CT-Rc[b]	17.7 Bns	17.8	17.1 b	16.7	15.6	15.6	16.5 Bns
	NT1-Rc	18.4 B	20.0	18.2 ab	17.4	16.9	16.7	18.6 B
	NT2-Rc	19.4 B	19.5	19.1 a	18.2	17.4	17.7	19.1 B
	NT3-Rc	19.9 B	20.2	19.3 a	18.2	17.4	17.4	19.3 B
5–10	RV	19.2 A	18.1 ns	17.2 ns	16.5 ns	16.7 ns	17.7 ns	21.6 A
	CT-Rc	16.0 BCns	16.1	15.1	15.3	14.8	14.9	15.8 Bns
	NT1-Rc	15.8 C	15.9	15.5	14.9	14.9	15.0	15.8 B
	NT2-Rc	16.9 ABC	17.1	16.2	15.9	15.5	15.8	16.5 B
	NT3-Rc	18.2 AB	18.7	17.5	17.3	16.4	17.2	17.5 B
10–20	RV	14.6 ns	15.0 ns	13.9 ns	12.5 ns	12.4 ns	13.1 ns	14.7 ns
	CT-Rc	14.6	13.8	13.2	12.9	13.1	12.7	13.0
	NT1-Rc	15.4	14.4	13.8	12.9	12.6	12.4	13.1
	NT2-Rc	14.5	13.9	13.3	13.3	13.2	12.8	13.4
	NT3-Rc	15.7	15.0	14.1	13.9	13.7	14.0	14.5

RV: reference vegetation; CT: conventional tillage; NT: no-till; Rc: rice; [a] Comparison between tillage systems CT-Rc, NT1-Rc, NT2-Rc, NT3-Rc and RV; Uppercase letters within the same column in each aggregate size class of each depth indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison among tillage systems CT-Rc, NT1-Rc, NT2-Rc and NT3-Rc; Lowercase letters within the same column indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 5.9

Concentrations of aggregate-associated total N (g kg^{-1}) in aggregate size classes under rice-based cropping systems

Depth (cm)	Land use	Aggregate size classes (mm)						
		8–19	4–8	2–4	1–2	0.5–1	0.25–0.5	0.053–0.25
0–5	RV[a]	2.57 A	2.24 ns	2.10 ns	2.06 ns	2.09 ns	2.24 ns	2.95 A
	CT-Rc[b]	1.76 Bns	1.86	1.74	1.65	1.64	1.66	1.70 Bns
	NT1-Rc	1.77 B	1.71	1.69	1.72	1.63	1.61	1.68 B
	NT2-Rc	1.83 B	1.89	1.76	1.75	1.74	1.70	1.91 B
	NT3-Rc	1.89 B	1.86	1.84	1.79	1.75	1.74	1.87 B
5–10	RV	1.92 ns	1.76 ns	1.67 ns	1.75 ns	1.75 ns	1.77 A	2.16 A
	CT-Rc	1.62	1.61	1.53	1.53	1.51	1.45 Cb	1.53 Bns
	NT1-Rc	1.65	1.61	1.51	1.55	1.53	1.53 BCab	1.61 B
	NT2-Rc	1.71	1.73	1.67	1.63	1.55	1.68 ABa	1.66 B
	NT3-Rc	1.73	1.73	1.70	1.71	1.61	1.64 ABa	1.74 B
10–20	RV	1.54 ns	1.58 ns	1.43 ns	1.39 ns	1.41 ns	1.44 ns	1.53 ns
	CT-Rc	1.54	1.45	1.38	1.45	1.38	1.35	1.39
	NT1-Rc	1.50	1.53	1.42	1.39	1.37	1.37	1.43
	NT2-Rc	1.58	1.54	1.48	1.44	1.44	1.41	1.53
	NT3-Rc	1.63	1.55	1.54	1.51	1.51	1.47	1.55

RV: reference vegetation; CT: conventional tillage; NT: no-till; Rc: rice; [a] Comparison between tillage systems CT-Rc, NT1-Rc, NT2-Rc, NT3-Rc and RV; Uppercase letters within the same column in each aggregate size class of each depth indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison among tillage systems CT-Rc, NT1-Rc, NT2-Rc and NT3-Rc; Lowercase letters within the same column indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 5.10

Concentrations of aggregate-associated POXC (g kg^{-1}) in aggregate size classes under rice-based cropping systems

Depth (cm)	Land use	Aggregate size classes (mm)						
		8–19	4–8	2–4	1–2	0.5–1	0.25–0.5	0.053–0.25
0–5	RV[a]	2.76 A	2.52 A	2.34 A	2.38 ns	2.33 ns	2.44 A	3.39 A
	CT-Rc[b]	1.79 Cc	1.76 Cc	1.77 Cb	1.71 c	1.68 b	1.72 Bb	1.75 Cb
	NT1-Rc	2.00 Cb	1.94 BCb	1.85 BCb	1.87 b	1.75 b	1.76 Bb	1.92 BCab
	NT2-Rc	2.28 Ba	2.19 ABa	2.17 ABa	2.13 a	2.07 a	2.08 ABa	2.18 Ba
	NT3-Rc	2.32 Ba	2.22 ABa	2.15 ABCa	2.10 a	2.13 a	2.05 ABa	2.14 BCa
5–10	RV	2.12 A	2.05 ns	2.04 ns	1.99 ns	1.97 ns	2.08 ns	2.28 A
	CT-Rc	1.69 Bns	1.76	1.70	1.68	1.64	1.65	1.68 Cb
	NT1-Rc	1.74 B	1.73	1.78	1.73	1.70	1.75	1.79 BCab
	NT2-Rc	1.89 B	1.97	1.88	1.82	1.73	1.78	1.87 BCa
	NT3-Rc	1.89 B	1.92	1.87	1.83	1.84	1.90	1.95 Ba
10–20	RV	1.90 ns	1.67 ns	1.68 ns	1.60 AB	1.57 ns	1.69 ns	1.70 ns
	CT-Rc	1.51	1.43	1.43	1.38 Cc	1.42	1.43	1.49
	NT1-Rc	1.62	1.59	1.53	1.50 BCbc	1.49	1.46	1.69
	NT2-Rc	1.74	1.66	1.58	1.63 ABab	1.59	1.64	1.75
	NT3-Rc	1.73	1.73	1.69	1.71 Aa	1.68	1.67	1.78

RV: reference vegetation; CT: conventional tillage; NT: no-till; Rc: rice; [a] Comparison between tillage systems CT-Rc, NT1-Rc, NT2-Rc, NT3-Rc and RV; Uppercase letters within the same column in each aggregate size class of each depth indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison among tillage systems CT-Rc, NT1-Rc, NT2-Rc and NT3-Rc; Lowercase letters within the same column indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 5.11

C management index (CMI) of aggregate size classes under rice-based cropping systems

Depth (cm)	Land use	Aggregate size classes (mm)						
		8–19	4–8	2–4	1–2	0.5–1	0.25–0.5	0.053–0.25
0–5	CT-Rc	65 c	70 b	76 b	74 c	74 b	73 b	51 b
	NT1-Rc	73 b	77 b	80 b	81 b	76 b	74 b	56 ab
	NT2-Rc	84 a	89 a	95 a	94 a	93 a	88 a	65 a
	NT3-Rc	86 a	89 a	93 a	91 a	95 a	87 a	64 a
5–10	CT-Rc	79 ns	86 ns	83 ns	83 ns	84 ns	80 ns	74 ns
	NT1-Rc	83	85	88	88	89	86	80
	NT2-Rc	89	97	92	91	89	86	83
	NT3-Rc	89	93	91	90	95	93	86
10–20	CT-Rc	80 ns	87 ns	85 ns	85 b	89 ns	84 ns	89 ns
	NT1-Rc	86	98	91	94 ab	95	86	103
	NT2-Rc	94	102	94	102 a	101	98	106
	NT3-Rc	94	109	104	109 a	108	100	108

CT: conventional tillage; NT: no-till; Rc: rice; Lowercase letters within the same column in each aggregate size class of each depth indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 5.12

Concentrations of aggregate-associated SOC (g kg^{-1}) in aggregate size classes under soybean-based cropping systems

Depth (cm)	Land use	Aggregate size classes (mm)						
		8–19	4–8	2–4	1–2	0.5–1	0.25–0.5	0.053–0.25
0–5	RV[a]	26.2 A	23.5 ns	21.9 ns	21.3 ns	21.5 ns	23.4 ns	29.3 A
	CT-Sb[b]	18.7 Bb	18.4 c	18.1	17.4	17.0	16.9	17.4 B ns
	NT1-Sb	20.0 Bab	20.4 ab	19.5	18.4	17.6	17.4	18.5 B
	NT2-Sb	20.1 Bab	19.1 bc	18.8	18.0	17.9	16.9	17.5 B
	NT3-Sb	21.2 Ba	20.9 a	20.0	18.7	17.9	17.5	19.7 B
5–10	RV	19.2 A	18.1 ns	17.2 ns	16.5 ns	16.7 ns	17.7 ns	21.6 ns
	CT-Sb	16.3 Cb	16.1	15.4 b	15.2	15.1	14.5	15.3
	NT1-Sb	17.9 ABCa	17.9	17.3 a	16.7	16.5	16.8	17.3
	NT2-Sb	17.2 BCab	17.1	16.5 ab	16.1	16.0	15.7	16.6
	NT3-Sb	18.1 ABa	18.6	17.9 a	17.6	17.3	17.4	18.1
10–20	RV	14.6 B	15.0 ns	13.9 ns	12.5 ns	12.4 ns	13.1 ns	14.7 ns
	CT-Sb	16.0 A ns	14.8	14.4	14.5	13.9	13.6	14.1
	NT1-Sb	16.6 A	16.5	15.9	15.6	15.5	15.6	16.1
	NT2-Sb	16.2 A	15.6	14.9	15.1	14.8	14.9	15.5
	NT3-Sb	16.2 A	15.5	15.0	15.0	14.8	14.7	15.0

RV: reference vegetation; CT: conventional tillage; NT: no-till; Sb: soybean; [a] Comparison between tillage systems CT-Sb, NT1-Sb, NT2-Sb, NT3-Sb and RV; Uppercase letters within the same column in each aggregate size class of each depth indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison among tillage systems CT-Sb, NT1-Sb, NT2-Sb and NT3-Sb; Lowercase letters within the same column indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 5.13

Concentrations of aggregate-associated total N (g kg^{-1}) in aggregate size classes under soybean-based cropping systems

Depth (cm)	Land use	Aggregate size classes (mm)						
		8–19	4–8	2–4	1–2	0.5–1	0.25–0.5	0.053–0.25
0–5	RV[a]	2.57 A	2.24 ns	2.10 ns	2.06 ns	2.09 ns	2.24 ns	2.95 A
	CT-Sb[b]	1.65 B ns	1.62	1.63 b	1.50	1.61	1.40 b	1.47 Bb
	NT1-Sb	1.80 B	1.77	1.68 b	1.70	1.67	1.61 a	1.66 Ba
	NT2-Sb	1.82 B	1.87	1.86 a	1.75	1.73	1.67 a	1.71 Ba
	NT3-Sb	1.90 B	1.84	1.77 ab	1.71	1.67	1.73 a	1.66 Ba
5–10	RV	1.92 A	1.76 ns	1.67 ns	1.75 ns	1.75 ns	1.77 A	2.16 A
	CT-Sb	1.37 Cc	1.38	1.31	1.31	1.30	1.30 C ns	1.41 B ns
	NT1-Sb	1.52 BCbc	1.53	1.53	1.48	1.47	1.42 BC	1.45 B
	NT2-Sb	1.67 ABab	1.68	1.67	1.54	1.56	1.63 AB	1.63 B
	NT3-Sb	1.77 ABa	1.76	1.65	1.68	1.65	1.69 AB	1.75 AB
10–20	RV	1.54 AB	1.58 ns	1.43 ns	1.39 ns	1.41 ns	1.44 ns	1.53 ns
	CT-Sb	1.36 Cb	1.33 bc	1.32	1.26	1.24 b	1.32	1.30
	NT1-Sb	1.38 BCb	1.29 c	1.30	1.30	1.26 b	1.21	1.24
	NT2-Sb	1.61 Aa	1.58 ab	1.54	1.49	1.52 a	1.52	1.51
	NT3-Sb	1.60 Aa	1.61 a	1.56	1.50	1.51 a	1.55	1.54

RV: reference vegetation; CT: conventional tillage; NT: no-till; Sb: soybean; [a] Comparison between tillage systems CT-Sb, NT1-Sb, NT2-Sb, NT3-Sb and RV; Uppercase letters within the same column in each aggregate size class of each depth indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison among tillage systems CT-Sb, NT1-Sb, NT2-Sb and NT3-Sb; Lowercase letters within the same column indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 5.14

Concentrations of aggregate-associated POXC (g kg^{-1}) in aggregate size classes under soybean-based cropping systems

Depth (cm)	Land use	Aggregate size classes (mm)						
		8–19	4–8	2–4	1–2	0.5–1	0.25–0.5	0.053–0.25
0–5	RV[a]	2.76 A	2.52 ns	2.34 ns	2.38 ns	2.33 ns	2.44 ns	3.39 A
	CT-Sb[b]	1.86 Cb	1.90 b	1.89	1.81	1.76	1.80	1.84 B ns
	NT1-Sb	2.27 Ba	2.27 a	2.22	2.15	1.98	2.09	2.15 B
	NT2-Sb	2.33 Ba	2.34 a	2.26	2.14	2.07	2.02	2.22 B
	NT3-Sb	2.38 Ba	2.35 a	2.28	2.14	2.12	2.12	2.30 B
5–10	RV	2.12 ns	2.05 ns	2.04 ns	1.99 ns	1.97 ns	2.08 ns	2.28 ns
	CT-Sb	1.83	1.86	1.75	1.75	1.75	1.79	1.88
	NT1-Sb	2.04	1.99	1.95	1.91	1.88	1.85	1.95
	NT2-Sb	2.29	2.15	1.89	1.82	1.79	1.88	1.88
	NT3-Sb	2.23	2.17	1.95	1.87	1.92	1.88	1.91
10–20	RV	1.90 ns	1.67 ns	1.68 ns	1.60 ns	1.57 ns	1.69 ns	1.70 ns
	CT-Sb	1.73	1.62	1.55	1.53	1.47	1.62	1.63
	NT1-Sb	1.88	1.85	1.85	1.81	1.77	1.95	1.77
	NT2-Sb	1.90	1.88	1.82	1.81	1.79	1.94	1.85
	NT3-Sb	1.92	1.86	1.85	1.78	1.99	1.89	1.94

RV: reference vegetation; CT: conventional tillage; NT: no-till; Sb: soybean; [a] Comparison between tillage systems CT-Sb, NT1-Sb, NT2-Sb, NT3-Sb and RV; Uppercase letters within the same column in each aggregate size class of each depth indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison among tillage systems CT-Sb, NT1-Sb, NT2-Sb and NT3-Sb; Lowercase letters within the same column indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 5.15

C management index (CMI) of aggregate size classes under soybean-based cropping systems

Depth (cm)	Land use	Aggregate size classes (mm)						
		8–19	4–8	2–4	1–2	0.5–1	0.25–0.5	0.053–0.25
0–5	CT-Sb	68 b	76 b	81	76 ns	76 ns	75 ns	54 ns
	NT1-Sb	83 a	91 a	97	94	87	90	64
	NT2-Sb	86 a	96 a	100	94	93	88	68
	NT3-Sb	88 a	95 a	100	93	95	91	69
5–10	CT-Sb	87 ns	92 ns	86 ns	89 ns	92 ns	90 ns	86 ns
	NT1-Sb	97	97	95	95	97	89	87
	NT2-Sb	112	108	92	91	92	92	83
	NT3-Sb	107	107	95	94	100	91	85
10–20	CT-Sb	93 ns	103 ns	94 ns	96 ns	94 ns	98 ns	98 ns
	NT1-Sb	100	113	110	112	111	117	103
	NT2-Sb	103	118	111	113	114	118	111
	NT3-Sb	104	117	113	112	128	115	119

CT: conventional tillage; NT: no-till; Sb: soybean; Lowercase letters within the same column in each aggregate size class of each depth indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 5.16

Concentrations of aggregate-associated SOC (g kg^{-1}) in aggregate size classes under cassava-based cropping systems

Depth (cm)	Land use	Aggregate size classes (mm)						
		8–19	4–8	2–4	1–2	0.5–1	0.25–0.5	0.053–0.25
0–5	RV[a]	26.2 A	23.5 A	21.9 ns	21.3 ns	21.5 ns	23.4 A	29.3 A
	CT-Cs[b]	16.3 B ns	16.4 B ns	15.9	15.1	14.8	15.0 B ns	15.7 B ns
	NT1-Cs	17.2 B	16.9 B	16.3	15.6	15.2	15.3 B	15.6 B
	NT2-Cs	17.6 B	17.4 B	16.7	15.6	15.4	15.5 B	16.2 B
	NT3-Cs	18.1 B	17.8 B	17.1	16.6	16.2	16.4 B	17.7 B
5–10	RV	19.2 A	18.1 ns	17.2 ns	16.5 ns	16.7 ns	17.7 ns	21.6 A
	CT-Cs	16.3 B ns	15.9	15.4	14.9	14.8	15.0	15.6 B ns
	NT1-Cs	16.1 B	16.0	15.4	14.7	14.7	15.2	15.9 B
	NT2-Cs	16.9 B	16.8	15.8	16.1	15.5	15.6	16.2 B
	NT3-Cs	17.8 AB	17.4	16.6	15.8	15.5	15.6	16.1 B
10–20	RV	14.6 ns	15.0 ns	15.0 ns	13.9 ns	12.5 ns	13.1 ns	14.7 ns
	CT-Cs	14.5	13.4	13.4	12.9	12.7	12.3	12.6
	NT1-Cs	14.1	13.9	13.9	13.5	13.2	13.2	13.7
	NT2-Cs	14.8	14.8	14.8	14.5	14.4	14.5	14.9
	NT3-Cs	15.6	15.4	15.4	15.0	14.6	14.8	15.1

RV: reference vegetation; CT: conventional tillage; NT: no-till; Cs: cassava; [a] Comparison between tillage systems CT-Cs, NT1-Cs, NT2-Cs, NT3-Cs and RV; Uppercase letters within the same column in each aggregate size class of each depth indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison among tillage systems CT-Cs, NT1-Cs, NT2-Cs and NT3-Cs; Lowercase letters within the same column indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 5.17

Concentrations of aggregate-associated total N (g kg^{-1}) in aggregate size classes under cassava-based cropping systems

Depth (cm)	Land use	Aggregate size classes (mm)						
		8–19	4–8	2–4	1–2	0.5–1	0.25–0.5	0.053–0.25
0–5	RV[a]	2.57 A	2.24 A	2.10 ns	2.06 ns	2.06 ns	2.24 ns	2.95 A
	CT-Cs[b]	1.54 B ns	1.52 B ns	1.46	1.41	1.40	1.35	1.47 B ns
	NT1-Cs	1.63 B	1.62 B	1.57	1.48	1.53	1.44	1.61 B
	NT2-Cs	1.79 B	1.84 AB	1.71	1.60	1.60	1.64	1.75 B
	NT3-Cs	1.82 B	1.81 AB	1.72	1.71	1.77	1.67	1.73 B
5–10	RV	1.92 ns	1.76 ns	1.67 ns	1.75 ns	1.75 ns	1.77 ns	2.16 A
	CT-Cs	1.54	1.57	1.54	1.39	1.45	1.41	1.48 B ns
	NT1-Cs	1.64	1.62	1.56	1.50	1.49	1.58	1.65 B
	NT2-Cs	1.69	1.70	1.58	1.47	1.47	1.44	1.59 B
	NT3-Cs	1.77	1.60	1.63	1.51	1.60	1.49	1.58 B
10–20	RV	1.54 ns	1.58 ns	1.43 ns	1.39 ns	1.41 ns	1.44 ns	1.53 ns
	CT-Cs	1.43	1.47	1.37	1.38	1.41	1.38	1.41
	NT1-Cs	1.49	1.46	1.40	1.46	1.40	1.40	1.49
	NT2-Cs	1.54	1.45	1.41	1.41	1.42	1.50	1.48
	NT3-Cs	1.67	1.60	1.53	1.50	1.51	1.47	1.62

RV: reference vegetation; CT: conventional tillage; NT: no-till; Cs: cassava; [a] Comparison between tillage systems CT-Cs, NT1-Cs, NT2-Cs, NT3-Cs and RV; Uppercase letters within the same column in each aggregate size class of each depth indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison among tillage systems CT-Cs, NT1-Cs, NT2-Cs and NT3-Cs; Lowercase letters within the same column indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 5.18

Concentrations of aggregate-associated POXC (g kg^{-1}) in aggregate size classes under cassava-based cropping systems

Depth (cm)	Land use	Aggregate size classes (mm)						
		8–19	4–8	2–4	1–2	0.5–1	0.25–0.5	0.053–0.25
0–5	RV[a]	2.76 A	2.52 A	2.34 ns	2.38 ns	2.33 ns	2.44 A	3.39 A
	CT-Cs[b]	1.85 Cb	1.77 Cc	1.85	1.84 b	1.76 b	1.77 Bb	1.79 Cb
	NT1-Cs	2.00 BCb	1.94 DCb	1.95	1.86 b	1.80 b	1.84 Bb	1.91 BCb
	NT2-Cs	2.26 Ba	2.19 BCa	2.14	2.14 a	2.08 a	2.16 ABa	2.25 Ba
	NT3-Cs	2.24 Ba	2.27 ABa	2.20	2.15 a	2.05 a	2.12 ABa	2.12 BCa
5–10	RV	2.12 ns	2.05 A	2.04 A	1.99 A	1.97 ns	2.08 A	2.28 A
	CT-Cs	1.70	1.69 B ns	1.66 B ns	1.56 B ns	1.51	1.56 B ns	1.62 B ns
	NT1-Cs	1.86	1.95 A	1.84 AB	1.80 A	1.80	1.82 AB	1.89 B
	NT2-Cs	2.03	1.93 A	1.81 B	1.82 A	1.76	1.85 AB	1.89 B
	NT3-Cs	2.08	1.94 A	1.86 AB	1.78 A	1.77	1.86 A	1.84 B
10–20	RV	1.90 ns	1.67 ns	1.68 ns	1.60 ns	1.57 ns	1.69 ns	1.70 ns
	CT-Cs	1.58	1.41	1.38	1.35	1.32	1.29	1.32
	NT1-Cs	1.69	1.74	1.64	1.73	1.73	1.71	1.62
	NT2-Cs	1.87	1.81	1.85	1.85	1.77	1.87	1.81
	NT3-Cs	1.81	1.75	1.71	1.63	1.69	1.81	1.74

RV: reference vegetation; CT: conventional tillage; NT: no-till; Cs: cassava; [a] Comparison between tillage systems CT-Cs, NT1-Cs, NT2-Cs, NT3-Cs and RV; Uppercase letters within the same column in each aggregate size class of each depth indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. [b] Comparison among tillage systems CT-Cs, NT1-Cs, NT2-Cs and NT3-Cs; Lowercase letters within the same column indicate difference between tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 5.19

C management index (CMI) of aggregate size classes under cassava-based cropping systems

Depth (cm)	Land use	Aggregate size classes (mm)						
		8–19	4–8	2–4	1–2	0.5–1	0.25–0.5	0.053–0.25
0–5	CT-Cs	68 c	71 b	82 ns	81 b	78 c	75 c	53 b
	NT1-Cs	74 bc	78 b	86	82 b	80 bc	78 bc	57 b
	NT2-Cs	85 a	90 a	94	95 a	94 a	94 a	68 a
	NT3-Cs	83 ab	93 a	98	96 a	93 ab	92 ab	64 a
5–10	CT-Cs	80 ns	82 ns	81 ns	77 ns	76 ns	74 ns	72 ns
	NT1-Cs	89	97	91	91	94	89	85
	NT2-Cs	97	94	88	91	91	89	84
	NT3-Cs	100	95	91	89	91	90	82
10–20	CT-Cs	86 ns	86 ns	82 ns	83 ns	83 ns	76 ns	78 ns
	NT1-Cs	91	108	98	110	111	102	96
	NT2-Cs	100	112	111	116	113	111	108
	NT3-Cs	98	109	103	102	107	101	104

CT: conventional tillage; NT: no-till; Cs: cassava; Lowercase letters within the same column in each aggregate size class of each depth indicate the difference among RV and tillage treatments at $P \leq 0.05$ by LSD. ns: not significant.

Table 5.20

Pearson correlation coefficients between aggregate-associated SOC over size classes and soil aggregation indices under rice-based cropping systems

Aggregate indices	Aggregate size classes (mm)						
	8–19	4–8	2–4	1–2	0.5–1	0.25–0.5	0.053–0.25
0–5 cm							
MWD	0.63*	ns	0.62*	ns	ns	ns	ns
MGD	0.66*	ns	0.65*	ns	ns	ns	ns
ASI	0.66*	ns	0.63*	ns	ns	ns	ns
5–10 cm							
MWD	ns	ns	ns	ns	ns	ns	ns
MGD	ns	ns	ns	ns	ns	ns	ns
ASI	ns	ns	ns	ns	ns	ns	ns
10–20 cm							
MWD	ns	ns	ns	ns	ns	ns	ns
MGD	ns	ns	ns	ns	ns	ns	ns
ASI	ns	ns	ns	ns	ns	ns	ns

n = 12 per aggregate size class for all soil aggregation indices; MWD: mean weight diameter (mm); MGD: mean geometric diameter (mm); ASI: aggregate stability index (%); * $P \leq 0.05$; ** $P \leq 0.01$; ns: not significant at $P \leq 0.05$.

Table 5.21

Pearson correlation coefficients between aggregate-associated SOC over size classes and soil aggregation indices under soybean-based cropping systems

Aggregate indices	Aggregate size classes (mm)						
	8–19	4–8	2–4	1–2	0.5–1	0.25–0.5	0.053–0.25
0–5 cm							
MWD	0.62*	ns	0.57*	ns	ns	ns	ns
MGD	0.63*	ns	0.58*	ns	ns	ns	ns
ASI	0.59*	ns	ns	ns	ns	ns	ns
5–10 cm							
MWD	ns	ns	ns	ns	ns	ns	0.64*
MGD	ns	ns	ns	ns	ns	ns	0.63*
ASI	ns	ns	ns	ns	ns	ns	ns
10–20 cm							
MWD	ns	ns	ns	ns	ns	ns	ns
MGD	ns	ns	ns	ns	ns	ns	ns
ASI	ns	ns	ns	ns	ns	ns	ns

n = 12 per aggregate size class for all soil aggregation indices; MWD: mean weight diameter (mm); MGD: mean geometric diameter (mm); ASI: aggregate stability index (%); * $P \leq 0.05$; ns: not significant at $P \leq 0.05$.

Table 5.22

Pearson correlation coefficients between aggregate-associated SOC over size classes and soil aggregation indices under cassava-based cropping systems

Aggregate indices	Aggregate size classes (mm)						
	8–19	4–8	2–4	1–2	0.5–1	0.25–0.5	0.053–0.25
0–5 cm							
MWD	0.75**	0.72**	0.64*	0.59*	0.66*	0.65*	ns
MGD	0.72**	0.70*	0.61*	ns	0.62*	0.61*	ns
ASI	0.77**	0.74**	0.68*	0.60*	0.66*	0.63*	ns
5–10 cm							
MWD	ns	ns	ns	ns	ns	ns	ns
MGD	ns	ns	ns	ns	ns	ns	ns
ASI	ns	ns	ns	ns	ns	ns	ns
10–20 cm							
MWD	ns	ns	ns	ns	ns	ns	ns
MGD	ns	ns	ns	ns	ns	ns	ns
ASI	ns	ns	ns	ns	ns	ns	0.61*

n = 12 per aggregate size class for all soil aggregation indices; MWD: mean weight diameter (mm); MGD: mean geometric diameter (mm); ASI: aggregate stability index (%); * $P \leq 0.05$; ** $P \leq 0.01$; ns: not significant at $P \leq 0.05$.

CHAPTER 6

General Conclusions

The association or rotation of cover crops with main crops under CA systems that produce high biomass inputs to the soil significantly increased total SOC in SbCS and CsCS in the surface soil layer and the recovery trend of SOC in RcCS under CA might become evident with time, particularly bi-annual crop rotations. The higher soil total N under CA in the three cropping systems also observed. Although SOC was higher in the few surface layers but a decrease in the deeper layers compared with CT was consistent. This might be related to the continuous supply of fresh C through root biomass and exudates from cover crops during six-month dry season, accelerating microbial activities that could decompose the native SOC with their enzymes using the source of energy from fresh C. It is likely that the studied heavy clayed Oxisols did not exhibit increased SOC in CT after five years due to soil texture, mineralogy and the biomass-C inputs returned to soils after the harvest of main (i.e., rice, soybean, cassava, maize) and preceding (i.e., mungbean, sesame) crops. However, a slight decrease in HWEOC and POXC was noticed, which might potentially affect the loss of total SOC in a longer period.

In general, CA increased the storage of labile SOC fractions (i.e., POC, HWEOC, POXC) and promoted soil enzymatic activities (i.e., β-glucosidase, arylsulfatase) especially at the 0-5 cm soil layer. These results emphasize the positive impact of short-term CA through the absence of soil disturbance and the importance of crops and their residues in accumulation of more SOC and its labile fractions and changes in the biological functioning of the soil, with higher soil enzyme activities in the topsoil. Thus, the labile SOC fractions and soil enzymes could serve as sensitive indicators of SOC dynamics in short-term CA practices. In contrast, MAOC, PEOC and CSOC were nearly constant in each depth among treatments in the three cropping systems, indicating less impacted or higher stability of these SOC fractions following short-term changes in tillage and crop rotation management. They represented the large portions of total SOC stocks.

The increased labile SOC fractions and soil enzyme activities under CA systems might partially contribute to an increase in soil aggregate stability and in turn SOC was physically protected and consequently to restore total SOC in the surface layers. Similar to RV, CA in the three cropping systems increased the proportions of large macroaggregates (8-19 mm) leading to an improvement of soil aggregation indices which positively correlated with the large macroaggregate-associated SOC. Even no significant effects in RcCS and SbCS, increased large macroaggregates and aggregate stability under CA play a crucial role in storage and stabilization of SOC, total N and POXC within macroaggregate-occluded microaggregates. The aggregate-associated POXC was more sensitive than SOC to the short-term CA systems resulting in greater concentrations in the majority of aggregate size classes than CT in the topsoil. It was supported by the results of CP-MAS ^{13}C NRM measurement that indicated the continuous biomass-C inputs under CA tended to increase the proportions of aliphatic C than under CT.

When comparing among the three CA systems, bi-annual crop rotations might be recommended as an appropriate crop rotation scheme that provided greater potential to restore total SOC, its labile fractions, soil enzymes, large macroaggregates and the concentrations of SOC, total N and POXC associated with large macroaggregates in the studied topsoil in a short-term period. Although deep rooting cover crops were included in the CA systems, it did not lead to a significant change in subsoil layers. However, the results support the concept of high potential to vertically distribute SOC to deeper layers over time resulting from the continuity of their high biomass-C inputs. The recovery trends of the majority of measured parameters were quite obvious in few subsurface soil layers as some significant differences were already apparent.

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